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THERMAL INSULATION FOR BUILDING CONSTRUCTION

Agricultural Research Service

UNITED STATES DEPARTMENT OF AGRICULTURE

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THERMAL INSULATION FOR BUILDING CONSTRUCTION

by

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I. INTRODUCTION

The object of this report is to determine the utilization potential of thermal insulating materials and to describe the performance requirements for some of the major end-uses in building construction. We believe that a description of the important properties of insulating materials now available and an outline of the areas for possible improvements can be of assistance in developing and appraising research projects that deal with industrial utilization of agricultural commodities. Because most of the agriculture-derived raw materials are of organic rather than inorganic origin, this report will not deal with industrial end-uses such as high-temperature furnaces, kilns, high-pressure boilers, high-pressure steam lines, metallurgical furnaces, roasters, flues, stacks, outer space activities, and other end-uses requiring temperatures which cannot be endured by insulating materials based upon most agricultural raw materials. On the other hand, data on building lumber will be included, although strength is its primary value, because its cost and insulating properties offer a well-established basis for comparison of commercial insulations.

II. INSULATION TERMINOLOGY

In any structure containing air spaces, there are three mechanisms of heat transfer: Conduction, radiation, and convection of the air. Typical insulation has very small spaces containing air or some other gas. Here, convection and radiation are minimized, but conduction employs parallel paths through the gas and through the solid lattice between cells.

Technical problems involving heat transfer require the use of a few typical terms, which are defined as follows:

Steady-state heat transfer through a body is a condition in which the temperature at any point within the body is constant, and heat outflow is equal to heat inflow. It is the simplest condition. Because it is the condition approximated in many practical applications of insulation, it is the condition presumed to exist when the term is used in this publication.

BTU is the abbreviation for British thermal unit and is generally used for engineering purposes. This unit of heat energy, added to 1 pound of water, will raise its temperature 1 degree Fahrenheit.

Thermal Conductance (symbol "C") is the time rate of steady heat flow through a unit area of a given body per degree of temperature difference between its parallel surfaces. The body

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may be homogeneous, or an assembly of several sheets, like the wall of a house. Conductance is measured in "BTU per hr., sq. ft., deg. F."

Thermal Conductivity (symbol "K") is the conductance of an essentially homogeneous body, 1 inch thick. If a body of different thickness is tested, its conductivity is the product of its conductance and thickness. Conductivity is a basic property of the material and is also called its "k-value." Unless otherwise stated, the k-value refers to a bone-dry material. Conductivity generally increases with increase in mean temperature and may be different on different axes of a fibrous material, depending on the "lay" of the fibers. Conductivity is measured in BTU per hr., sq. ft., (deg. F. per in.). In building construction, a mean of 75° F. is suitable for comparisons.

Surface Coefficient (symbol "f" or "h"), as applied to buildings, is the rate of heat transfer to or from a solid surface in contact with air. This transfer includes radiation (except from the sun) as well as the thickness implied by the nature of the surface, its orientation, and the rate of air motion. In still air, the coefficient of a typical horizontal surface ranges from 1.08 BTU per hr., sq. ft., deg. F. for downward heat flow to 1.63 BTU for upward heat flow. A reflective surface in still air has a much lower surface coefficient, and a 15 m.p.h. wind increases the coefficient for any exterior surface to 6.0. (ASHRAE Guide and Data Book)

Thermal Transmittance (symbol "U") is the air-to-air conductance of a body multilayer assembly (such as a wall) with air on each side. It is conventional in most locations to consider the exterior air velocity as 15 m.p.h. The transmittance of a wall ceiling, roof, or other system or assembly is also called its "U-value," and sometimes its "Overall Coefficient of Heat Transfer." Note that "U", "h", "C", and "k" all apply to unit time and unit area normal to the heat flow.

Thermal Resistance (symbol "R") and Thermal Resistivity (symbol "y", "R" per inch of thickness): All the terms noted earlier in this section are related to the conductance of heat, and these are the terms generally used. Another set of terms relates to the resistance to heat flow. Resistance is the inverse of conductance and each resistance term may be defined as the reciprocal of its corresponding conductance term. A calculation of the conductance of an assembly of two or more slabs or sheets requires the addition of all their resistance values, and then reconverting the total resistance to the overall conductance. For example, if C_1, C_2 and C_3 are the conductance values of three sheets, their combined resistance (in contact) is:

$$R = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

or

$$R = R_1 + R_2 + R_3$$

and their combined conductance is:

$$C = \frac{1}{R}$$

It is evident that the manipulation would be simplified if the thermal values of materials were stated in resistance terms, and progress is being made in this direction, but it is hampered by established customs. However, the resistance unit called "ru" does simplify the terminology, as follows:

Resistance, $R = \frac{1}{C}$ or $\frac{1}{U}$ and is measured in "ru".

Resistivity, $y = \frac{R}{s} = \frac{1}{k}$ and is measured in "ru/in.", where s = thickness.

To suggest the magnitude of these units, the air-to-air resistance of a typical frame wall with wood sheathing and empty stud spaces is 4.2 ru, and its "U-value" is 0.24 BTU per (hr.) (sq. ft.) (deg. F.).

If the stud space is filled with a typical fibrous insulation, the air-to-air resistance is increased to 17.2 ru and its U-value is reduced to 0.058 BTU per (hr.) (sq. ft.) (deg. F.).

Thermal Cost Index (TCI). Depending upon the type of insulation, prices are generally quoted in one of the following ways:

a. Batts and blankets are sold on a dollars-per-1000-sq.-ft. basis. Manufacturers also specify thickness as well as "R-value" which is the resistance of each thickness.

b. Loose fill is sold on a dollars-per-bag basis. Manufacturers usually indicate that a bag may, for instance, weigh 25 lbs. and could cover an area of 115 sq. ft., 4 1/2" thick. (A similar weight of a more dense material may cover only 50 sq. ft., 4 1/2" thick.) There is also a growing trend in the industry to include R-value for a specified thickness or depth of fill.

c. Rigid insulation boards are made in a variety of sizes and finishes. They are sold on the basis of dollars per thousand square feet of a given thickness. A growing number of suppliers of roof insulating board also specify the thermal conductance (C-value) or resistance (R-value). Semi-rigid boards and expanded foam compositions are frequently sold by the board foot measure (a board foot is 1" x 12" x 12") with k-values and densities given.

In an attempt to determine the prices at which a new competitive product would have to sell in order to gain commercial acceptance, a "Thermal Cost Index" (TCI) has been devised. The use of this index enables us to express the cost in terms of true insulating value. TCI is measured in dollars per 1000 sq. ft., ru. This expression shows the cost of 1000 sq. ft. of the insulation of such thickness that it has a unit resistance--one ru. To obtain the TCI of any product, divide the cost of 1000 sq. ft. by its thermal resistance (R-value). The result is in "dollars per 1000 sq. ft. ru."

For example, take two insulating materials, "A" and "B":

"A" is 3/4" thick, has a conductance C = 0.33, and is priced at $60 per 1000 sq. ft. Its resistance is $R = \frac{1}{C} = \frac{1}{0.33} = 3.0$ ru, and its TCI is $60 divided by 3.0 = $20 per 1000 sq. ft., ru.

Insulation "B" is 2" thick, has a resistance "R" = 7 ru and is priced at $100 per 1000 sq. ft. Its TCI is $100 divided by 7 = $14.30 per 1000 sq. ft., ru.

Obviously insulation "B" with its lower TCI is the less expensive material from the standpoint of effective thermal resistance. Installation cost and other physical properties should also be considered.

Water Vapor Transmission. The rate of water vapor transmission through insulation and other associated materials, under the specific conditions of use, should always be considered in the design of buildings. The water vapor permeability of an insulation is one of its important properties and is measured in "perm-inches." A perm-inch is one grain per sq. ft., hr., (inch of mercury per inch of thickness).

The permeance of any given thickness is expressed in "perms." ASTM C-355-63T describes the test procedure.

III. GENERAL REQUIREMENTS FOR THERMAL INSULATION

A. Basic requirements

In heated buildings and/or air-conditioned buildings, thermal insulation is used for two primary reasons: Comfort and economy. Where heating fuel is cheap, comfort the year round is apt to be of primary importance. On the other hand, where electric heating and/or air-conditioning equipment is employed, the emphasis is on economy. In any event, it is not difficult to prove that an adequate amount of thermal insulation cuts both winter heating and summer cooling costs.

The economic thickness of a given insulation is reached when the annual investment cost of any additional thickness exceeds the saving obtained thereby. The saving considers all operating costs of heating and/or cooling (if used) and the investment in equipment. Throughout much of the U.S. about 6 inches of insulation in the ceiling and three in the walls is desirable, although the range of winter climate from Florida to Minnesota may justify a range in insulation thickness from zero to 8 inches.

Thickness is, of course, only one criteria. A 6" batt can have an R = 19 ru value, while 8" of blowing wool (loose fill) may be required for 19 ru. Thickness, thermal resistivity, and type of insulating material are all involved.

Comfort involves the surface temperature of walls, floor, and ceiling areas (and drafts caused thereby) as well as the inside air temperature. Insulation is an effective means of raising the inside winter temperature of these surfaces, thereby improving the comfort of a person lightly clothed, especially when seated near the wall where a downward cool air current may be expected if there is no low-level heat source.

As an example, consider a typical frame wall home that has an interior air temperature of 73° F. in zero weather. If the wall has the normal wood sheathing and empty stud spaces, the temperature of the interior gypsum surface will be about 63° F. at the 6 ft. level, and 54° F. at the 1 ft. level (7),[3] and a cold draft comes down the wall and around the ankles. The large difference of 9° F. between top and bottom is caused by natural air motion within the wall cavity.

Filling the 3 1/2" wall cavity with insulation (k = 0.27) will raise the interior surface temperature to 70° F., and reduce the difference in temperature between high and low levels to a small amount. The heat loss is reduced 76%, and air convection within the wall is virtually eliminated. Raising the surface temperature of the wall also reduces the relative humidity near it and avoids the risk of dust patterns and possible stains by surface condensation.

In a warm climate, an air-conditioned building requires insulation to reduce the cooling costs--both operating and investment charges. In most areas of the United States, a building with a flat roof like that of a supermarket has a cooling load in summer that is larger than the heating load in winter. When the sun is bright, the rooftop may have a temperature as high as 160° F., or 80° higher than the interior temperature, producing a heat inflow in summer that is larger than the outflow in winter when outdoor temperature may be 0° F. While occupancy is high, many schools, theaters, and other public buildings need little winter heat but need a high cooling capability in summer. Insulation significantly reduces the cooling load.

Special constructions, such as refrigerated storage, that operate under a continuous load at a temperature that is moderately above or far below freezing justify more insulation per degree of temperature difference. Moreover, insulation often deteriorates in such structures. The loss of insulating value is caused by the entrance of moisture and its accumulation as water and/or as ice within the insulation. Structural failure of insulation also occurs when a heavy ice develops.

The migration and condensation of water vapor is a problem of major importance in many buildings. It is especially damaging in refrigerated construction where the vapor flow may be always inward, and unless strictly limited, the accumulation of this moisture ultimately becomes serious. In a temperate climate, seasonal weather may reverse the vapor flow in buildings and allow the cycle to start anew each winter. Condensation is a hazard that demands proper consideration of the problems involved. Temperature-humidity relationships vary with the seasons, and materials used in construction vary in resistance to the transmission of water vapor. In any event, condensation in the wall or ceiling is a potential source of serious damage so long as it remains in the system. (15)

[3] Underscored figures in parentheses refer to Bibliography at the end of this report.

B. Practical requirements

Many practical considerations are involved in the acceptance of insulation for a particular application. These considerations are as follows:

1. Durability of essential insulating properties:
   a. Thermal resistance as installed.
   b. Shape, structure, and density (with the elasticity and compressive strength needed for the application).
2. High thermal resistivity, or "thinness per ru," which may be more important than cost where space is strictly limited.
3. Moisture tolerance. Building insulation immune to the effects of moisture under any and all conditions has not been produced, but proper moisture control makes any insulation satisfactory. Moisture damages the structure more than it damages the thermal value of insulation. Moisture's effect on insulation performance depends largely on its state, as follows:
   a. Hygroscopic moisture. Swelling, shrinking, and warping due to absorption of water from the air are hazards to structural insulation as well as to framing. Mold may be expected in organic material unless it contains a proper fungicide. Organic insulating materials are generally more hygroscopic than inorganic materials, but reduced thermal insulating value due to hydroscopic moisture is rarely excessive.
   b. Free moisture. Liquid water, unlike hygroscopically bonded water, increases heat transfer markedly. Water not held by capillarity flows downward through porous insulation to a lower level where it may be safely drained or dangerously retained.
   c. Ice. Expansion of water into ice may cause structural damage. Freezing, partial thawing, and refreezing cause a cyclic ice buildup that can be very damaging. Ice is a major problem in cold storage insulation if insufficient attention is given to vapor flow. Furthermore, as ice builds up progressively, it increases heat transfer and cannot be removed without stopping refrigeration.
   d. Vapor. Vapor adds but little to heat transfer while it is in the vapor state. If vapor condenses in the colder parts of the insulation, it causes the effects noted previously. Vapor control should be planned by reducing the entrance of vapor and/or by improving its exit from insulation. A one-perm (1 gr. per hr., sq. ft., in. mercury) vapor barrier is generally adequate for the walls in residential construction where the outside wall is a good "breather." Buildings used for laundries or paper manufacturing, those having flat roofs without a ventilated loft, and cold storage installations (4) require special attention.
4. Structural strength, which is important for certain applications, especially for sheathing of homes.
5. Low in cost (low Thermal Cost Index).
6. Low installation cost and easy handleability, including fast, reliable installation by machine or semi-skilled labor, and low transportation and storage costs.
7. Fire resistance. Requirements depend on building size, location, and occupancy. Local codes are variable, but all insulation should be fire resistant.
8. Light in weight which may also be a requirement for certain applications where the load must be limited. (Items 2 and 8 apply especially to mobile homes and vehicles that are heated or refrigerated.)
9. Vermin resistance. Local practice and codes apply. Termite damage can be serious in the South.

The question of how much insulation should be used and where to use it in a building is always a problem. Geographic and climatic conditions, fuel costs, and the properties of available insulation are governing factors. For example, the insulation industry has recommended that for electrically heated and air-conditioned homes the installed insulation should have the resistance

TABLE 1.--Thermal Values for Electrically Heated and Air-conditioned Homes

(Recommended by National Mineral Wool Association and the All Weather Comfort Standard Committee)

Area	Maximum transmittance of the assembly-- U-value[1]			Minimum resistance of insulation-- R-value[1] [2]		
	Quality homes	Economy standard	Minimum comfort standard	Quality homes	Economy standard	Minimum comfort standard
Ceilings	0.05	0.07	0.10	19	13	9
Walls	0.07	0.09	0.11	11	8	7
Floors over unheated spaces	0.07	0.09	0.11	12	9	7

[1] Values are dependent on local climate. These are for temperature differences encountered in the Washington, D.C. area.

[2] The minimum resistance (R) excludes the resistance of structural members, such as plaster ceilings, wall sidings, and wooden floors.

values shown in table 1. For the outside walls and roofs of refrigerated warehouses, good practice (5) suggests development of an overall heat transfer coefficient, "U" from 0.035 to 0.05 for freezers and from 0.05 to 0.75 for coolers, or between coolers and freezers.

It is also important to know where in a building the greatest relative heat losses and gains can be expected to occur. As an example, consider the following figures for a "typical" uninsulated two-story house with a basement. (9).

	Winter Losses	Summer Gains
Walls	33%	34%
Ceilings and Roof	22%	24%
Floors	1%	4%
Glass and Doors	30%	26%
Infiltration	14%	12%

A single-story home with the same floor area would have double the ceiling area and a somewhat reduced wall area. A home further north or south would also show somewhat different percentage relationships. But in any case, it is apparent that insulation in the walls and ceiling offers the greatest opportunity to control heat losses or gains.

C. Test methods

A compilation of the various ASTM specifications, methods of test, and recommended practices, as formulated by Committee C-16 on Thermal Insulating Materials was issued in March 1962. An excellent section on experimental methods, with many drawings, can be found in USAF Technical Documentary Report No. ML-TDR-64-5 entitled "Thermophysical Properties of Thermal Insulating Materials" issued in April 1964. In addition there are numerous Federal Specifications listing test methods and/or referring to other established test methods. Specifications are constantly being studied and revised as better and/or cheaper materials become commercially available.

IV. END-USE CLASSIFICATION

There are literally hundreds of end uses for insulating materials, but for the sake of simplicity we have divided them into seven major groups:

1. Residential buildings
2. Industrial and farm buildings
3. Cold storage warehouses
4. Process industries (Equipment and Pipes)
5. Appliance industry
6. Transportation
7. Miscellaneous

As indicated in table 2, each of these groups may be further subdivided to show the application of various competing forms of insulation material. The requirements for building insulation are different for the walls, ceilings, roofs, and perimeters below ground level. The type and form of insulating material required for each of these applications depends upon geographic location, weather conditions, ease of installation (labor cost), and the amount of insulation desired for minimum or maximum comfort or protection. Structural requirements, such as load-bearing capacity and other features determined by type of outside wall (brick, concrete, stone, wood, etc.), may also be considered in selecting the insulation system.

Most producers of ready-to-use thermal insulation avoid the confusion (and added cost) of marketing separate products for each potential end use. They market their materials in three broad categories:

1. Nonrigid insulation
   a. Batts, blankets and rolls
   b. Loose fill

TABLE 2.--End-Use Classification for Thermal Insulation Products

End Use	Type of insulation					
	Batts or blankets	Loose fill	Structural board	Blocks	Foamed plastics	Structural panels
1. Residential Buildings:						
Walls	x	x	x		-	x
Ceiling	x	x	x	-	-	-
Roof	x	-	x	-	-	-
Perimeter	-	-	-	x	x	-
2. Industrial and farm buildings: (Walls, ceilings, roofs, perimeters)	x	x	x	x	x	x
3. Cold Storage Warehouses: (Walls, ceilings, roofs, perimeters)	-	-	-	x	x	x
4. Process Industries Equipment: (Pipes, tanks, boilers and miscellaneous equipment for chemical, petroleum, food and other industries)	x	-	x	x	x	-
5. Appliances: (Refrigerators, ovens, dishwashers, etc.)	-	-	x	-	x	x
6. Transportation: (RR, ships, trucks)	x	-	x	x	x	x
7. Miscellaneous: (Clothing, ice rinks, swimming pools, greenhouses, etc.)	x	x	x	x	x	-

2. Rigid insulation
   a. Structural insulation
   b. Nonstructural shapes
3. Reflective

Most products in these categories can meet the performance requirements of a great number of end uses. For instance, insulating batts and blankets and boards can be used to protect walls, roofs, ceilings and floors in residential as well as industrial buildings. Batts and boards are also used extensively in cold storage warehouses, the process industries, and the transportation industry.

V. MARKETS AND POTENTIALS

The market for thermal insulation has been growing rapidly in recent years. Without stretching market dimensions to include products such as clothing, the industry can logically be characterized as being in the billion dollar a year category. The use of insulation in refrigerated buildings, frozen food processing plants, and wholesale food warehouses has increased due to a seven-fold increase in freezer production during the past decade, and this growth is expected to continue for another 10 years. The use of insulation in residential construction more than tripled between 1940 and 1950. In 1940, only one new house in four used ceiling insulation, and one in ten had wall insulation. Today wall and ceiling insulation are as common as indoor bathrooms.

The types and amounts of insulation employed for different end uses vary. Mineral wool, for example, is employed in all phases of building construction, process equipment insulation, and wherever limitation of heat transfer is desirable. It may be supplied as loose fill, or packaged in felt, batt, or blanket form, or in combination with other materials molded into boards, blocks, or sandwich-type panels.

Detailed market statistics on the major types of insulation are not available for specific end uses. The major buyers use a variety of materials in the construction of buildings, and the reasons for their choices differ. Moreover, the choice of insulating material for a given end use usually involves a compromise among desirable features, including cost.

The total market for insulation materials whose production is reported to the U.S. Department of Commerce is shown in figure 1. The $700 million total represents sales by manufacturers. The ultimate buyer pays in excess of a billion dollars annually for thermal insulation materials.

This total includes not only thermal insulation used in buildings but also materials designed for usage above 500° F., insulation for power plants, industrial processing equipment, and such original equipment applications as used in household appliances and in truck-trailer, railroad, and marine outlets. Many of these uses require specially designed insulation forms, but their inclusion in figure 1 does not materially alter the ratios that apply to the building insulation market.

A. Insulation for building construction

Thermal insulation is applied to or within the walls, ceiling, or roof, under the first floor in buildings without basements, and in cold storage buildings to prevent the passage of heat and, in certain cases, to avoid warm-side surface condensation. The insulation is made of (1) fibrous material, such as mineral wool, glass fiber, and vegetable or animal fiber; (2) reflective material, such as aluminum foil; (3) expanded vermiculite ore or perlite; or (4) plastic or glass foam and

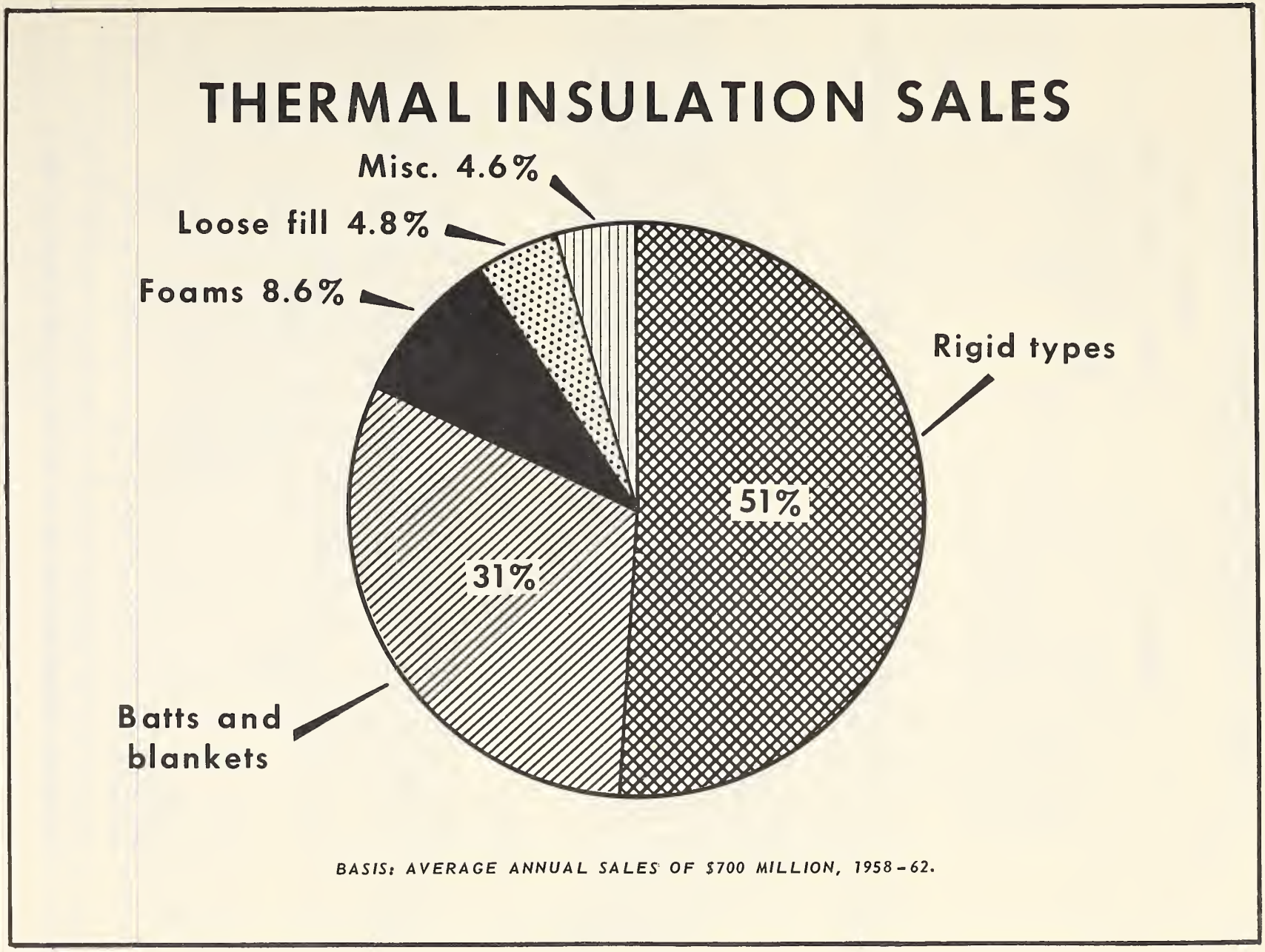
THERMAL INSULATION SALES
Misc. 4.6%
Loose fill 4.8%
Foams 8.6%
Rigid types
51%
31%
Batts and blankets
BASIS: AVERAGE ANNUAL SALES OF $700 MILLION, 1958-62.

Figure 1

TABLE 3.--Estimated Sales of Insulation to Building Industry Outlets

Physical Form	Current annual sales
	Millions of dollars
Batts and blankets	120
Loose fill	15
Structural insulation board	70
Other boards and blocks	75
Prefabricated units	20
Total	300

corkboard. These materials, singly or in combination, are marketed as insulation in a variety of forms and sizes classified as follows:

1. Blankets, batts, and rolls;
2. Loose fill;
3. Structural insulation board;
4. Other boards and blocks;
5. Miscellaneous.

This classification is used in table 3 to present estimates supplied by leading insulation manufacturers, the National Insulation Manufacturers Association, and the Insulation Board Institute (6, 11, 12). ("Structural insulation board," as here used, applies to large sheets made from wood or cane fibers having important structural strength, fastened by nailing. "Other boards and blocks" are made from mineral fibers or foamed materials, including glass, plastics, and cork. The "Miscellaneous" category includes reflective materials, prefabricated panels, etc.)

B. Trends in home insulation

According to Ralph Johnson of the National Association of Home Builders, the use of insulation in home construction has increased substantially in recent years. It was little used before World War II, and then mainly in ceiling construction. A survey by the U.S. Dept. of Labor (19) indicated the situations shown in table 4 existed in the average new one-family, nonfarm house:

TABLE 4.--Residential Houses with Insulation

Area	1940	1950	1956
	Percent	Percent	Percent
Ceiling	25	83	81
Walls	10	34	33
Perimeter	n.a.	1	5

The survey's breakdown of the figures for 1950 and 1956 is given in Table 5.

TABLE 5.--Residential Insulation Distribution by Type of Insulation

Type of insulation	Walls		Ceiling	
	1950	1956	1950	1956
	Percent	Percent	Percent	Percent
Batts and Blankets	[1] 43	70	[1] 95	44
Loose Fill	([1])	5	([1])	48
Structural Board	32	5	2	1
Blocks	n.a.	n.a.	n.a.	n.a.
Foamed Plastics	n.a.	0.5	n.a.	0.5
Reflective (foil only)	25	7	2	2
All other or unknown	--	13	1	5
Total (all types)	100	100	100	100

[1] Data for loose fill and batts and blankets in 1950 are combined.

The figures in tables 3 and 5, coupled with current industry figures, indicate not only a growth in use of insulation in residential construction but also that:

a. Batts and blankets (rolls) predominate in wall insulation holding at least 70% of the single-family house wall insulation.
b. Loose fill is far more apt to be used for ceiling insulation than for wall insulation of new houses, but until recently it has been the only type available for existing, uninsulated house walls. Foamed-in-place materials may alter this situation.
c. The drop of Structural Board to 5% of the market for the walls of new homes in 1956 is far below the share reported by industry (11, 12, 13) and suggests that the survey reporters did not consider that structural insulation board is wall insulation as well as a strength member. Actually, insulating boards have been displacing a great deal of lumber and gypsum board used for sheathing, roof insulation, and interior wall construction because they combine structural and insulating values.
d. Foamed plastics and structural insulation panels are now used in residential as well as in industrial building applications.
e. Reflective sheets without "mass insulation" are not as widely used as in the past, but a reflective cover that functions as a vapor barrier on a fibrous blanket is widely used.

The decreasing use of ordinary lumber is homebuilding since 1940 was noted in the 1956 study by the U.S. Dept. of Labor (19). Insulation board and plywood have been taking the place of lumber for sheathing in many frame houses. Plywood competes with lumber for subflooring, siding, and dry-wall finish. Built-up roofs and the greater use of asbestos and asphalt shingles have cut deeply into the market for wooden shingles. A sharp reduction in the use of wooden lath occurred with the substitution of wallboard as the interior finish or as a base for plaster.

However, lest the foregoing comments give a negative picture on use of natural wood, it should be noted that housing and other building construction still take a major share of the production of wood-base materials (13). Growth in the use of these products is well illustrated by the fact that softwood plywood production was 10.8 billion square feet (3/8-inch basis) in 1963 compared with 7.8 billion square feet in 1960 (4 billion board feet versus 2.9 billion board feet)--a 39% increase in volume consumed. Similar increases are noted in the consumption of hardwood plywood and hardboard.

In addition to the basic considerations of thermal resistance, the wind resistance of a wall assembly should also be considered. Air infiltration is minimized by sheet materials like coated insulation board, plywood, and hardboard.

A basic assumption for calculations of market requirements is that the average new, one-family (nonfarm) house has one story, with an estimated insulation requirement of 1000 sq. ft. for walls and 1200 sq. ft. for the ceiling. Multi-family, multi-story dwellings (apartments, etc.) need an average of about 300 sq. ft. of ceiling insulation per family unit, but such dwellings have little need for wall insulation. Approximately one million single-family houses and 500,000 multi-family housing units are started annually in the U.S. (as of 1962) (18). A further assumption is that sidewalls use insulation averaging 2 inches thick, while ceiling insulation averages 3 inches thick, exclusive of structural insulating board (sheathing, etc.).

These assumptions lead to the conclusion that the total current potential per year in new housing units amounts to the equivalent of about 6 billion board feet of insulating materials.

C. Refrigerated storage

Refrigeration is employed in the processing, transporting, and warehousing of many types of foods and beverages, in addition to its employment in the field of frozen foods and household storage. Industrial applications include skating rinks, concrete dams, subsurface soils and foundations, industrial liquid cooling, photographic processing, the manufacture of ice, etc.

Refrigerated installations require special attention to insulation and vapor barriers. Dependability and overall costs of construction and operation govern choices to an even greater extent than they do in normal building construction (5).

No statistics on tonnage consumption of insulating materials used in this field are available, but it is estimated that construction of cold storage facilities increased seven-fold within the past decade. In terms of relative volumes of insulating material now being employed, polystyrene foam ranks high, with other foams (plastic, glass and cork) also important. Mineral wool (including glass fiber) batts and blankets have special merit in refrigerated vehicles and in combination with foams for low temperature applications.

VI. BATT AND BLANKET INSULATION

A. General description

Batt and blanket insulations are made from processed fibers such as mineral wool (including rock, slag or glass types) or vegetable fibers such as cotton or wood, and even animal hair. Each type finds extensive use in building construction. Batts of standard length up to 4 feet and of various thicknesses are supplied in cartons. Blanket insulation is generally sold as a long, tightly rolled ribbon that is easily cut to the required lengths on the job. Some very elastic fibers permit a 6 in. thickness, often used in ceilings, to be shipped in a compact roll that regains its normal thickness when applied.

A reflective surface--perforated aluminum foil or coated paper--on the top side of insulation facing an open attic or loft is particularly valuable to resist summer heat entrance into the room below (10).

Excepting poured or blown-in-place material, batts and blankets provide two of the simplest forms of fibrous insulation. They are shaped to fit in standard spaces between the framing of walls (fig. 2) or ceiling and are easily compressed to fill a nonstandard space. One or both faces may be covered by paper adhered to the fibers, improving handleability and giving adequate support within a wall construction before the interior finish is applied. Batts and blankets are easily installed and require special fittings only where pipes or wires obstruct the framing space.

BLANKET INSULATION WITH VAPOR BARRIER COVER

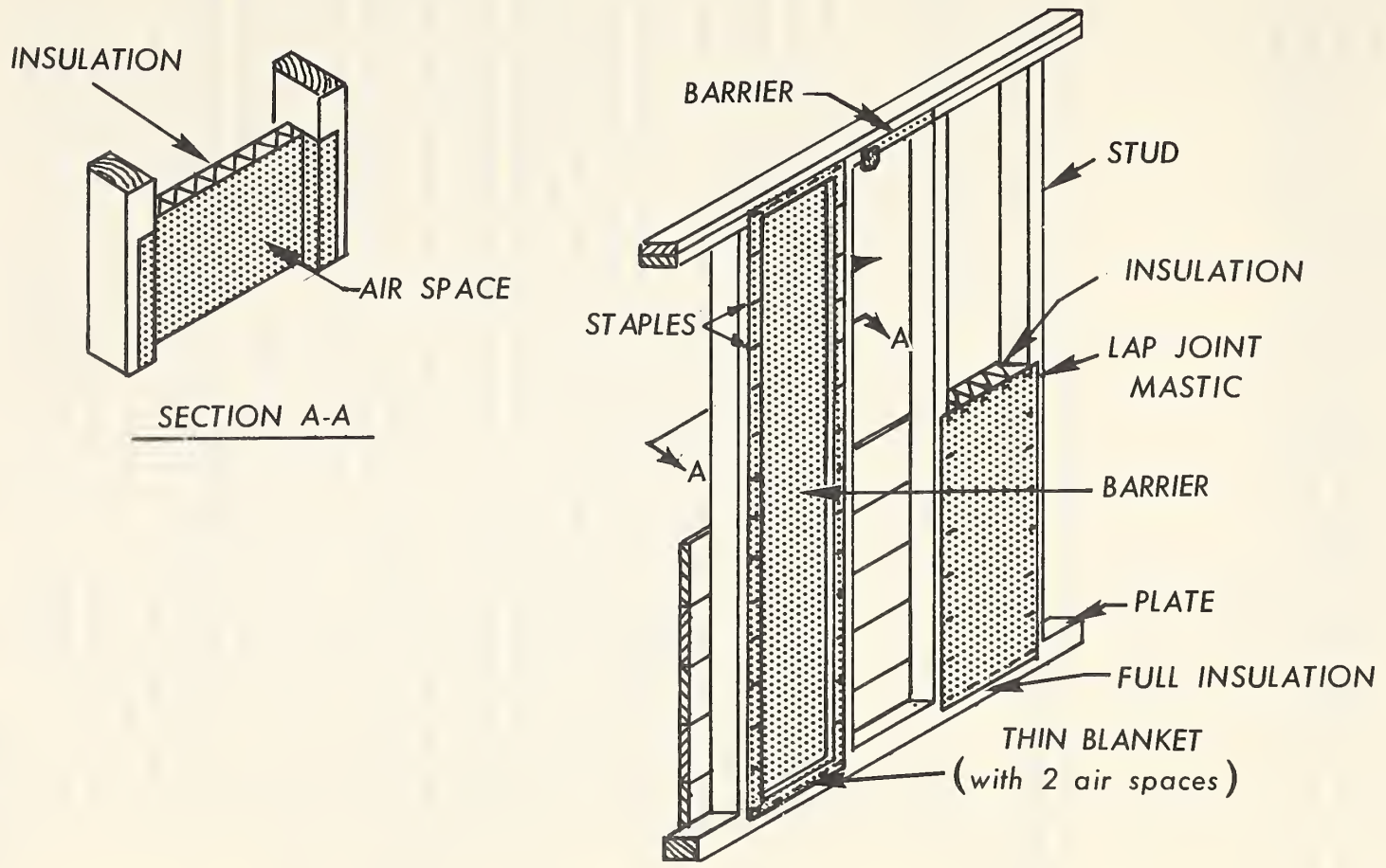

Figure 2

Two features, frequently offered, are an integral vapor barrier on the warm side (toward the room), and designed placement in the middle of the stud space so that two air spaces are obtained with added insulating value, especially if one or both faces are reflective. Unfortunately, these good features are largely lost if each space is not fully closed to any air exchange (7). In recognition of this fact, there is a trend toward a thicker blanket and a separate plastic vapor barrier that can be more dependably applied as a large sheet covering the whole wall. For use in a ceiling, the batts and blankets may carry an integral vapor barrier to limit vapor entrance to the cold attic, and in this application, an imperfect barrier is acceptable when the attic floor is not tight and the attic will be ventilated.

B. Significant properties

The important properties and performance requirements of batts and blanket type insulating materials are shown in table 6 (3). The right-hand column has the range of properties within which a new insulating batt or blanket material would normally fall in order to gain commercial acceptance:

1. Density. Typical densities range from 0.8 to 2.0 lbs./cu. ft. for cotton-based insulating material, and from 1.5 to 3.6 for wood fiber insulating materials. Mineral wool batts and blankets are sold in densities varying from 0.3 to about 4 lbs./cu. ft. The very lightweight products offer versatility, good resiliency and flexibility at some sacrifice of thermal efficiency, due to internal air convection. One of the advantages of the blanket design is that the insulating fibers are enclosed and attached to the paper (or other) casings, thus permitting a rather low density of insulation in vertical wall spaces without excessive settling. Since the cost of the insulation is largely dependent upon the amount of fibers used, the blanket type insulation enables the builder to provide the desired thermal insulation (R-value) at a relatively low cost.
2. Thermal resistivity ($y = \frac{1}{k}$) is one of the most important properties of insulating materials. The ultimate dream of the heating and refrigeration engineer would obviously be a material having a very high thermal resistivity (4 ru per inch or higher) combined with a low Thermal Cost Index. Such a material would find a wide application wherever only limited space is available. Most of the commercial batts and blankets, however, have thermal resistivities between 3 and 4 ru per inch and this is adequate to provide the needed thermal resistance (R-value) within the space available between the 2" x 4" studs in new homes.

The thermal resistivity of each type of bulk insulation varies moderately with density. For fibers of a given size, the resistivity increases to a maximum value at some higher density where the decreasing size of air cavities is offset by the increasing heat paths through the solid lattice. But a low density insulation is improved by reducing the fiber size, thus reducing air convection and its molecular freedom.

3. Water absorption and vapor permeability. Insulating materials provide the maximum thermal resistivity when they are dry, though hygroscopic moisture has a relatively small effect upon their insulating value. Plant fibers are much more hygroscopic than mineral fibers and may hold as much as 20% moisture (by weight) with no serious loss of thermal value. Free water is more serious. If it fills the small spaces between fibers, the low conductivity of air is replaced by the high conductivity of water. Any insulation having a fine porous structure will retain liquid water (or ice) that entered as a liquid or as a vapor that condensed in its colder parts. If these hazards are properly avoided in design and construction, the water absorption[4] of an insulation is not one of its vital properties.

[4] ASTM C-209 provides a test for "water absorption" of structural insulation board, which is often subject to rain or snow during construction.

TABLE 6.--Properties of Batts and Blankets

Property	Cotton fiber	Mineral wool[1]	Wood fiber	Probable features of a new product
Density, lb./cu. ft.	0.8 - 2.0	0.3 - 4.0	1.5 - 3.6	Range of 0.5 to 4.0
Thermal Conductivity (k) at 75° F.	0.26	0.27-0.33	0.25	0.17 - 0.50
Thermal Resistivity (y) ru per inch at 75° F.	3.8	3.0 - 3.7	4.0	2 - 4
Vapor Permeability, perm-inch.	70	90	80	10 - 100
Resistance to Termites, Fungi.	([2])	Good	([2])	Very important, particularly in southern United States
Maximum Service Temperature °F.	250	About 450	250	200 or higher
Fire Resistance.	([2])	Good	([2])	Good resistance
Typical Wholesale Price: Dollars per 1,000 bd. ft.[3]	$25	$15	--	Depends upon thermal resistivity and other desirable features
Thermal Cost Index ($/1,000 sq. ft., ru)	$6.50	$4-5	--	$3.00 to $5.00

[1] Fibrous form processed from rock, slag or glass.
[2] Additives improve resistance to these hazards.
[3] Prices based on data from several manufacturers; use quoted prices only as indications.

The vapor permeability of fibrous insulation is naturally high, and this is desirable when a proper barrier limits vapor entrance to a rate which will safely pass through the fibrous structure and escape to the weather without condensation. In the United States, a 1-perm barrier coupled with a 5-perm exterior wall covering has been found satisfactory for typical house walls. With this combination, the permeability of the insulation (if not zero) should be at least 10 perm-inches, giving the necessary permeance to a blanket of the maximum thickness that can be placed in a $3\frac{1}{2}$-in. wall cavity. Avoidance of condensation damage involves climate, usage, and all details of construction (3).

4. Resistance to vermin. A material like mineral wool is immune to attack by termites and fungi, and so are its usual binders, asphalt and resins. Plant fibers and some binders require treatment to resist vermin and thus qualify for thermal insulation. Below the ground level, only blankets made from mineral materials are considered satisfactory.
5. Dimensional stability. As far as batts and blankets are concerned, dimensional stability is not important since they are not expected to contribute to the structural characteristics of the building. Flexibility, on the other hand, is important and test specifications are given, which include bending batts and blankets over a round object a prescribed number of times without damage to the material.
6. Maximum service temperature. For most of the structures in which batts and blankets (including binders and additives) are used, a maximum service temperature of 200-250° F. is adequate.
7. Fire resistance. In recent years, the demand for fire-resisting construction materials has increased. For this purpose special treatments are often necessary.

C. Economics

The wholesale carload prices of most batts and blankets are usually quoted in dollars per 1000 square feet and depend upon the following factors:

1. Thickness--ranges from 1/2" to 6 1/4".
2. Thermal resistance (R-value)--ranges (from 2 to 24).

3. Type of facing--double foil, one side vapor permeable or asphalt kraft paper, etc.
4. Nature of the material--mineral wool, rock wool, glass wool, slag wool, cotton, wood fiber, etc.

The market for thermal insulation is highly competitive, and many excellent products are being sold by a great number of companies. The competitive position of any product involves all its features, but a primary consideration is likely to be its price per unit of insulating value, or Thermal Cost Index (TCI), as previously defined in Section II. For example, a 2-1/4" thick mineral wool blanket with an R-value of 9 ru that sells for $36 per 1000 square feet (i.e., $16.00 per 1000 bd. ft. with y = 9/2.25 = 4 ru/in.) would have a Thermal Cost Index of $4 per 1000 sq. ft., ru.[5]

Blankets and batts are notable for their low Thermal Cost Indexes, which range between $4 and $6.50 per 1000 sq. ft., ru. If properly installed, they provide excellent thermal resistance (high R-value) at relatively low cost.

In figure 3, the upward sloping lines of constant TCI indicate the rising wholesale price per 1000 bd. ft. that is justified by increasing resistivity alone. For example, the $4 TCI line indicates that a blanket having a thermal resistivity of only 2 ru per inch, and selling for $8 per 1000 bd. ft., would offer the same insulating value as one having a resistivity of 4 ru and selling for $16 per 1000 bd. ft. However, with increasing thermal resistivity, the competitive price of the insulation could probably increase somewhat faster than that indicated by the TCI line, a possibility brought forth in the shaded area shown in figure 3. For example, in electrically heated homes it is important to concentrate a high degree of thermal resistance in a limited space, i.e., "thinness per ru" is worth more money when space is valuable. It has been estimated (8) that 20 million U.S. homes will be electrically heated in 1980 as compared with only 2 million in 1963. (This growth will naturally require both adequate insulation and more attention to ventilation needs.)

The cost of installing insulation (labor and equipment) varies widely, depending upon the type of structure, the location, labor market, and other factors. Batts require no installation tools other than a stapler or hammer and a knife or shears. Thick blankets without a vapor barrier may be installed in the same way. A thick blanket in a wall cavity requires stapling to hold it in proper position, and if a vapor barrier is a part of the blanket, good workmanship is essential (7). Carpenters who usually do this work can staple up to 1500 sq. ft. per 8-hour day at a labor cost of about $20 per 1000 sq. ft. A contractor's charge for installing blanket insulation between 2" and 4" studs is reported to average between 70 and 90 dollars per 1000 sq. ft. This figure includes both labor and materials.

Desirable future improvements of batts and blankets should include one or more of the following:

1. Less installation labor or skill.
2. Lower material cost.
3. Materials with higher thermal resistivity, or lower TCI values (fig. 3).

The shaded section in figure 3 indicates the logical area where development may be expected.

VII. LOOSE-FILL INSULATION

A. General description

This type of insulation is in a loose granular, flake, or fibrous form. Loose-fill insulation is particularly adaptable for insulating existing buildings as well as ceilings in new construction (fig. 4). There are two types of loose-fill insulation: (1) the pouring type, which can be poured

[5] 1000 sq. ft. of batt or blanket, placed between the studs of a typical frame wall, will cover 1100 sq. ft. of wall area, exclusive of windows and doors. These uninsulated areas combine with air infiltration to increase the total heating load of a building.

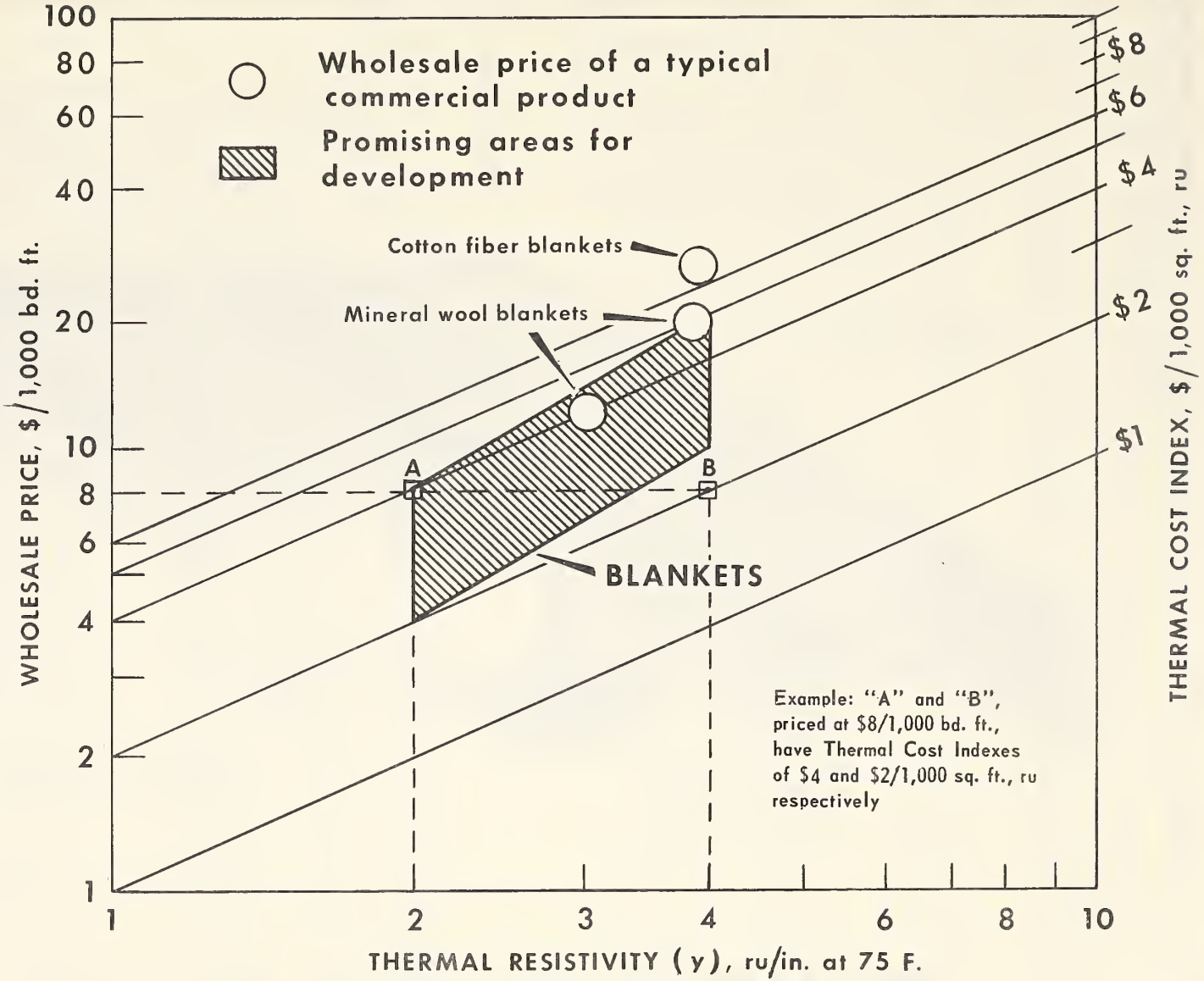

Figure 3. --Cost of blanket insulation.

LOOSE FILL INSULATION

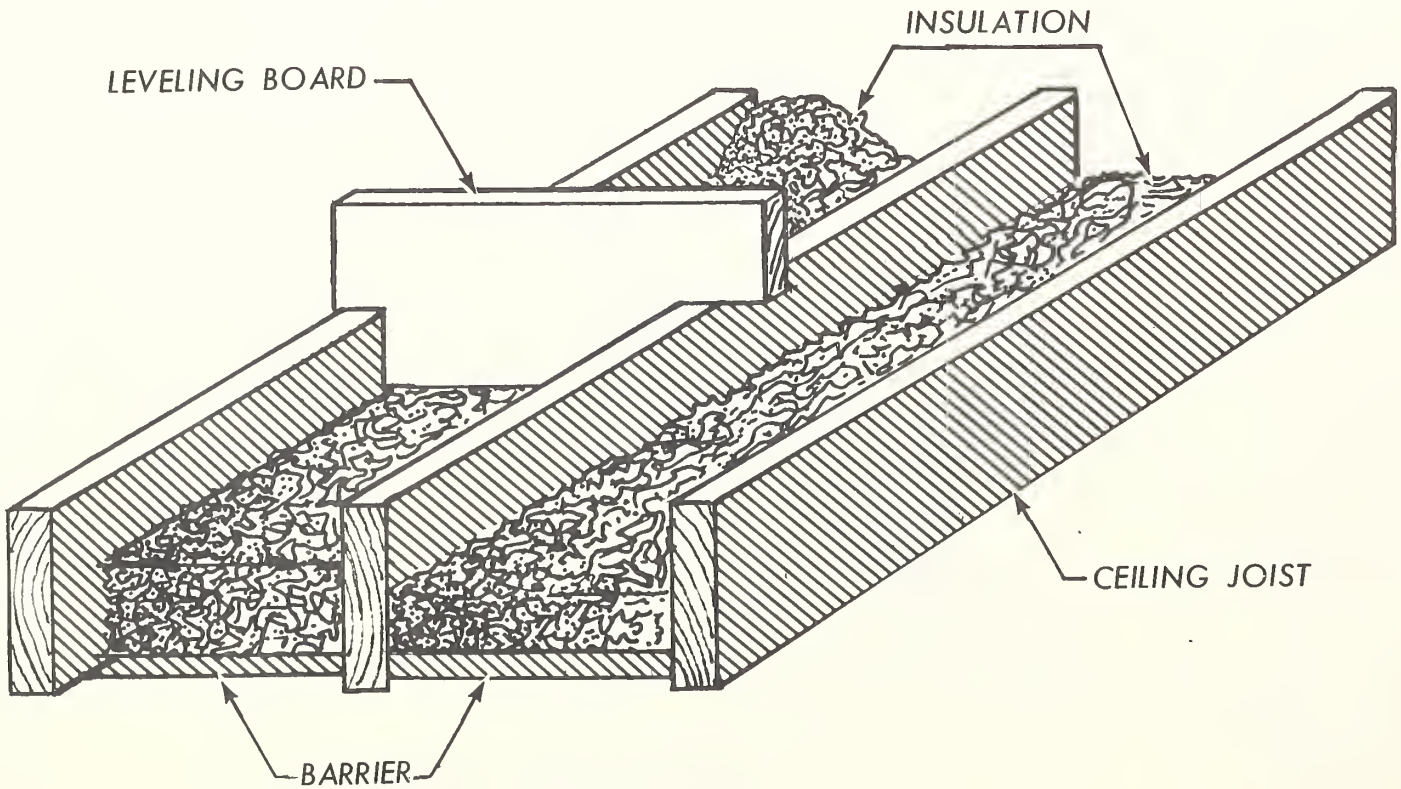

Figure 4

directly from the bag into the space to be insulated, and (2) the blowing type, which is blown in place with the aid of suitable equipment.

A possible disadvantage of both types is the fact that they tend to settle with time if the installed density is low--below 7.5 lbs./cu. ft. In a wall, this would leave an empty uninsulated pocket. For this reason loose fill must be applied so that uniform density and sufficient density is obtained to prevent settling. Loose fill is used in buildings (other than cold storage facilities) for insulating walls, ceilings, and all openings such as those around electric outlets, vent pipes, and chimneys.

In order to provide good thermal insulation, loose-fill fibrous materials normally contain dead-air spaces, which serve as buffers to the flow of heat. A great variety of materials can be employed, among them being vermiculite, glass wool, silica, other mineral wools, cotton, animal hair, wood, cork, and even paper. It is also possible that several other agricultural raw materials could be utilized to make loose-fill insulation.

A fluffy, wool-like material can be made from redwood bark, which is defibered, impregnated, fluffed, dried, and especially processed to assure proper felting characteristics. The processed material is actually made up of cellular fibers of controlled size, is fire resistant, will not deteriorate, will not be affected by usual moisture variations, will not provide sustenance for rodents and vermin, and is guaranteed to last as long as the structure.

Fill-type insulation offers little resistance to water vapor penetration. In new construction, a proper vapor barrier may be easily installed. The addition of fill-type insulation in the walls of an existing building generally increases the condensation potential. A careful assessment of this hazard may indicate the need for more ventilation near vapor sources and possibly a vapor-resisting paint coat as a barrier on the interior of walls.

B. Significant properties

The more important properties of a number of different loose-fill insulating materials are shown in table 7. Many of these properties are based upon data in ASHRAE Guide and Data Book, 1963, page 399.

1. Density. This property ranges from 0.6 for pouring mineral wool to 15 for sawdust. In general, the lower the density, the greater the coverage, but the highest thermal resistivity is usually obtained at some intermediate density.
2. Thermal resistivity. This property usually ranges between 3 and 4 ru per inch for most loose-fill materials. In selecting a suitable loose-fill insulating material, it may be necessary to sacrifice resistivity in order to achieve a gain in other important properties such as improved fire resistance and higher service temperatures, as illustrated by expanded vermiculite.
3. Water absorption and vapor permeability. Requirements are similar to those of batts and blankets.
4. Resistance to termites and fungi. Requirements are similar to those of batts and blankets.
5. Maximum service temperature. For homes and most buildings a maximum service temperature of 200° F. to 250° F. is adequate. Mineral material should be used when higher temperatures are required for industrial equipment and pipe insulations.
6. Fire resistance. (See "Batts and Blankets.")

C. Economics

The wholesale prices for most loose-fill insulation are generally quoted in dollars per bag. For example, a blowing-wool product may be quoted (wholesale) at $2 per bag and designed to cover adequately a net area of 115 sq. ft. (between joists), in a layer 4½" thick, and provide a

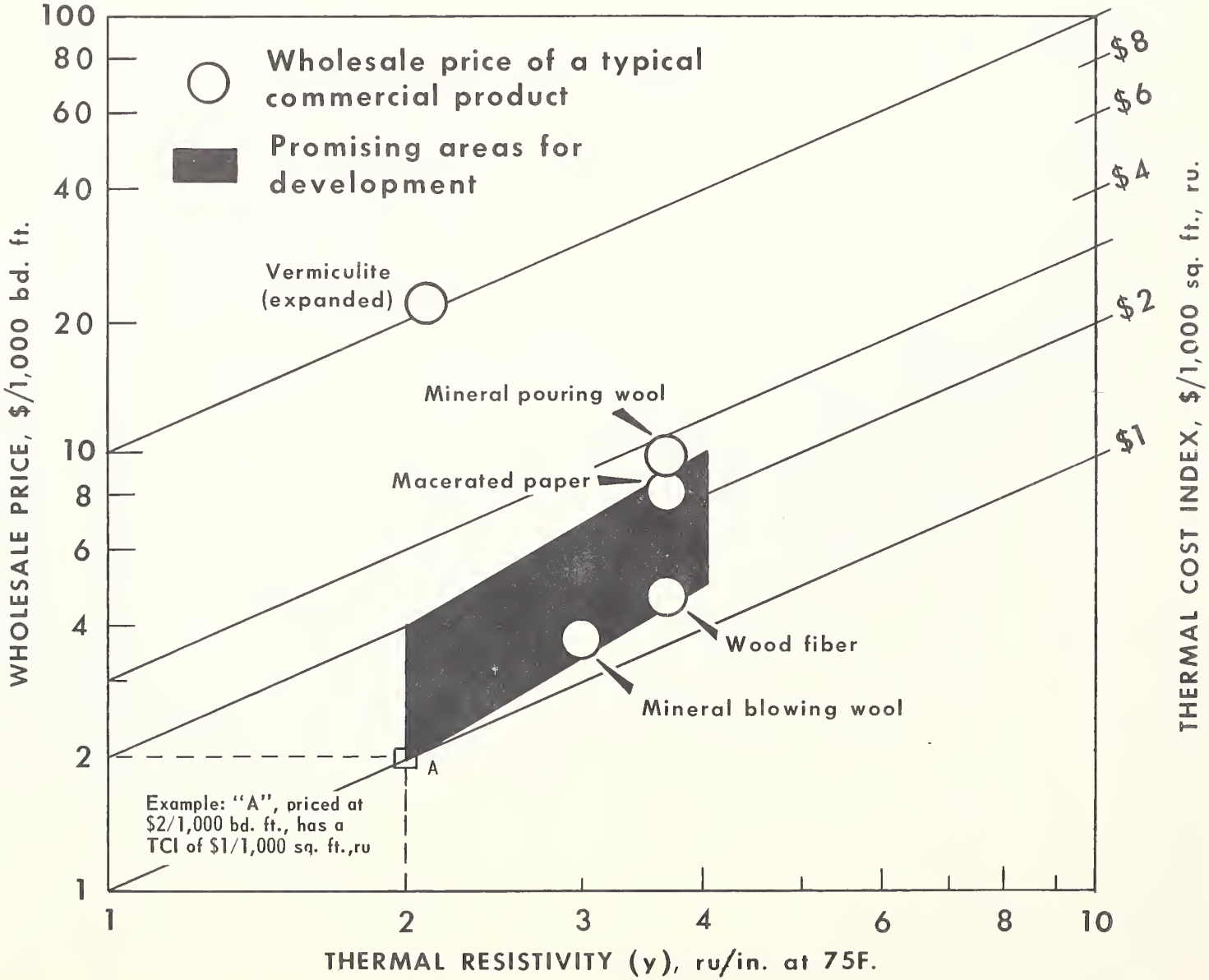

Figure 5. --Cost of loose-fill insulation.

TABLE 7.--Properties of loose-fill insulation

Property	Macerated paper or pulp product	Mineral wool[1]		Vermiculite expanded	Wood Fiber[2]	Probable features of a new product
		Blowing	Pouring			
Density, lb./cu. ft.	2.5 - 3.5	2.6-3.0	3.0	4-6	1.5-3.5	0.5 - 15
Thermal Conductivity (k) at 75° F.	0.28	0.3-0.34	0.28	0.48	0.28	0.30 or lower
Thermal Resistivity ru per inch at 75° F.	3.6	2.9-3.3	3.6	2.1	3.6	2 - 4 ru per inch
Water Absorption, % by weight	--	low	low	< 9	up to 36	
Vapor Permeability, perm-inch	40	90	90	50	80	> 10
Resistance to Termites, Fungi	([3])	Good	Good	Good	([3])	Good
Maximum Service Temperature, ° F.	250	450	450	2000+	250	200° F. or higher
Typical Wholesale Prices Dollars per 1000 board feet	$8.00	$3.87	$10.00	$23.00	$4.67	Depends upon thermal resistivity (see Fig. 5) and low cost application
Thermal cost index ($/1000 sq. ft., ru)	2.24	1.25	2.80	11.00	1.31	$1 - $3

[1] Glass, slag or rock; higher density is also obtainable.
[2] Redwood, hemlock or fir.
[3] Additives improve resistance to these hazards.

thermal resistance of 13 ru. If these figures are converted to the common denominator (TCI) for all insulating materials, they indicate a price of $3.87 per 1000 board feet, and a thermal cost index of $\frac{\$3.87\ 4\frac{1}{2}"}{13\ ru} = \$1.34$ per 1000 sq. ft., ru. The prices of loose-fill are shown at the bottom of table 7 but should be considered only as approximate because of the rather wide variations in density and resultant coverage that may be applied.

In order to gain commercial acceptance, a new insulating material of the loose-fill type presumably should meet the following requirements:

a. Thermal cost index of about 1 to 3 dollars per 1000 sq. ft., ru. (see figure 5).
b. Thermal resistivity of 2 to 4 ru per inch.
c. Good resistance to termites and fungi.
d. Maximum service temperature 200° F. or higher (for buildings).
e. Fire resistance is desirable but not strictly essential.
f. Easy installation and good durability (see chapter on "General Requirements").

VIII. RIGID INSULATION MATERIALS

A. General description

Rigid insulation materials are manufactured as "boards," and thicker "blocks" for a wide variety of applications. A wide assortment of organic and inorganic raw materials are employed in their manufacture, with the primary objective being to combine practical form and adequate strength with thermal insulating values. Ideally, the products should be as strong as steel, light as a feather, and have a high thermal resistivity. Somewhere between these objectives, compromises have to be made to meet the specific needs of each end use.

1. Structural Insulation Board. This category covers felted, homogeneous or laminated boards or sheets manufactured from ligno-cellulosic fibers and/or fiber bundles. The manufacturing process is somewhat similar to the process for making paper products. The board is generally made from processed wood (e.g., Southern pines and aspen) or sugar cane (bagasse) fibers and may be called by such names as insulating board, fiberboard, wallboard, or other trade names.

   Boards made of wood or cane fiber are specifically fabricated for specific end uses. The products are also treated to resist wetting, insects and fungi. In addition, all products designed for interior finish uses have flame-resistant surfaces. These products are made in densities that range from 10 to 26 lbs./cu. ft. The primary purpose of some of these products is structural strength in building construction; others provide fashionable beauty and/or sound control for interior use. The outstanding feature of insulating boards compared to "particle board" and ordinary lumber is that they have lower density and provide higher thermal insulating value. As construction products, they are easy to saw, nail, staple, glue, and paint.
2. Mineral Fiber Board. Fiber boards made from mineral wool, including glass fiber, provide another kind of answer to such problems as fire resistance, atmospheric humidity, and fungal resistance. The materials used therein may be fused and drawn, flame-blasted or spun into fibers of consistent physical and chemical composition. With organic or inorganic binders, they are molded into rigid or semi-rigid boards. They are normally produced at densities in the range of 6 to 24 lbs. per cu. ft., and are used in a variety of applications.
3. Plastic Foam Insulation. The cellular structure and consequent large number of dead air spaces have made plastic foams popular insulating materials. Rigid plastic foams generally provide low thermal conductivity, high strength-weight ratio, low odor, ease of handling, and simple fabrication. Some have good resistance to water vapor. While many types normally do not provide the high structural strength of typical fiber boards, the rigid foams do possess greater rigidity and compressive strength than batts, blankets, and loose-fill types of insulation.

   Semi-rigid foams, like certain other types of non-load-bearing boards and blocks, offer an intermediate range of values. Flexible foams can be used as blanket, batt, pipe, or loose-fill thermal insulation where structural strength is not required.

   Foamed plastics that can be molded to fit the contours of a structure are particularly suitable for insulation in refrigerators, freezer cabinets, trailer bodies, railroad refrigerator cars, airplanes, low temperature industrial piping, and air conditioning equipment.

   Foams are produced by extrusion or molding, and are also foamed-in-place. Rigid polystyrene and polyurethane foams, either extruded or molded, are supplied in a variety of shapes. They have been used in building construction much longer than other foam types (silicones, phenolics, epoxies, etc.) that are still considered specialties or developmental. As boards and blocks, plastic foams are produced in a range of densities. They can be made fire-retardant or self-extinguishing when specially formulated (20). Apart from the question of relatively high cost for materials of limited structural strength, urethane foams containing a low-conductivity gas have a remarkably high y value (low k) but show a loss in thermal resistivity with age, particularly when exposed to air. This problem is being tackled by the manufacturers.

   The foamed-in-place (or poured-in-place) type of plastic foam, exemplified by the polyurethane foams, can be rigid or flexible. Technically, these foams are thermosetting cellular materials prepared at the use site either by hand or machine mixing of the components of the particular system. They can be readily prepared in a wide range of densities, with closed or open cell structure, for a growing variety of applications, including the building of self-supporting structures (1).

4. Miscellaneous Types. This category includes a variety of insulation materials differing in physical shape or origin or in field of usefulness from the types just described.

Cork insulation, derived from the bark of the cork oak grown principally in Spain and Portugal, is no longer produced in the United States. The granulated cork bark is formed into blocks or boards by use of heat and pressure. Very popular at one time, it is still considered by many building contractors as the standard for comparison of insulating boards (table 8).

Gas-filled (H_2S) cellular glass and cellular rubber find special applications as thermal insulation because they are essentially impervious to water and water vapor. Cellular glass is also impervious to common acids and acid fumes. These materials are used principally in the construction of cold storage rooms and for specialty applications, including underground insulation (tables 8, 9, and 12). Cellular rubber is employed for the insulation of cold piping; cellular glass is used where high vapor resistance and rigidity are required. In such special applications, unique properties tend to offset high insulation costs.

B. Properties of rigid and semi-rigid board insulations

The important properties of rigid insulation boards and plastic foams are shown in tables 8 and 9. For the purposes of comparison, typical values have been selected despite differences among specific commercial products. Both thermal and mechanical properties, usually tied rather closely to the basic composition and density, also vary with cell size or fiber size and in the type and amount of binder (if any). In accordance with established practice, thermal values apply only to "bone-dry" materials.

TABLE 8.--Properties of Rigid Insulations[1]

Property	Product and major use							Probable features of a new product
	Cellular glass[2]	Cork board	Glass fiber	Wood or cane fiberboard			Shredded wood[5]	
	Cold storage		Various	Interior	Roof	Sheathing	Roof deck	
Density, lbs./cu. ft.	9 - 11	6.5 - 8.0	9.5 - 11.0	12	16	20	22	8 - 20
Thermal Conductivity (k) at 75° F.	0.39	0.28	0.27	0.34	0.36	0.38	0.55	0.4
Thermal Resistivity (y) at 75° F., ru per inch, average	2.6	3.7	3.7	2.9	2.8	2.6	1.8	2.5 - 4.0
Water Absorption:								
% by weight	0	[6] 3.0	[6] 18	52	39	22	3.6	Below 30
% by volume (4)	0.2	2.1	1.0	10	10	8	2.9	Below 3
Vapor Permeability (dry cup), perm-inch, average	0	2.5	50	25	25	20 [4] 5	30	Needs vary
Resistance to Termites, Fungi	Perfect	[3] A	Good	A	A	A	Good	Good resistance
Dimensional Stability (linear expansion)(4)	Excellent	Good	Good	0.5%	0.5%	0.5%	--	
Maximum Service Temperature, °F.	800	200	450	200	250	250	250	200° F. or higher
Fire Resistance	Excellent	Fair	Good	A	A	A	A	Good resistance
Compressive Strength, av. at 5% deformation, min. psi at failure	100	--	[7] NS	[8] NE	--	NE	--	
Modulus of Rupture, psi	--	--	NS	← 250 - 700 →			--	End-use experiences govern choice
Flexural Strength, min. psi	75	15	NS	--	--	6000	--	
Modulus of Elasticity in Bending, psi	--	--	NS	← 25,000 - 90,000 →			--	
Tensile Strength, minimum psi (4):								
Parallel to surface	NE	NE	NE	150	150	150	--	Minimum of 150 psi
Perpendicular to surface				4	4	4	--	Minimum of 3.5 psi
Typical Wholesale Price: Dollars per 1000 bd. ft.	$120	$100	$100	$80	$80	$78	$55	Depends upon resistivity and structural properties
Thermal Cost Index ($/1000 sq. ft., ru)	46	28	27	27	29	30	30	$20 - $30

[1] For foamed materials see Table 9.
[2] Average values adapted from ASTM Specification C343-56.
[3] Additives improve resistance to these hazards.
[4] Value for fiberboard from ASTM Specification C208-60.
[5] Cemented in preformed slabs.
[6] Building Research Advisory Report No. 38(5).
[7] NS not specified.
[8] NE not essential in most applications

TABLE 9.--Typical Properties of Foam Insulation Materials[1]

Property	Polyurethane		Polystyrene		Epoxy (pour or spray)	Phenolic (reactive)	Cellulose acetate	Polyvinyl chloride	Neoprene	Probable features of a new product
	Closed cell[2]		Extruded	Molded						
Density at 75° F., lb. per cu. ft.	1.5 - 3.0	9 - 12	1.6-4	1-5	[2]1.8-2.3	2 - 5	7	4 - 25	10 - 30	Below 5 lbs./cu.ft. for insulation only; higher density where structural strength is paramount
Thermal Conductivity (k) at 75° F.										
Blown with CO_2	0.23	0.33	0.23-0.26	0.28	0.25	0.21-0.28	0.31	0.27-0.36	0.28-0.45	Below 0.32 where space is limited; higher k-value is acceptable when associated with structural needs
Blown with FC[3]	0.11-0.17	0.25	---	---	0.17	---	---	---	---	
Thermal Resistivity, ru per inch at 75° F.										
Blown with CO_2 (or other low mol. wt. gas)	4.3	3.0	3-4.3	3.6	3.6	3.6-4.3	3.2	2.8-3.7	2.2-3.6	See above
Blown with FC[2]	5.9-8.3	4.0	---	---	5.9	---	---	---	---	
Water Absorption, % by volume	4	1	2	5	---	---	7	---	---	Not important in most applications except where freezing is a danger.
Water Vapor Transmission, perm-inch	2	1	2-1	5-2	2-1	20	high	---	---	Both high and low permeabilities have merit for particular uses
Tensile Strength, psi	15-70	350	40-120	50-150	30-60	35	170	---	20-100	15 psi minimum for most uses
Compressive Strength, psi @ 10% deformation	15-50	450	10-120	[4]8-50	15-40	50	125	---	---	Above 15
Special feature	Tight cell structure		---	---	adhesive	---	High buoyancy			
Coefficient of Linear Expansion, 10^{-5} in/in/°F	4	6	3.5	3.5	0.8	1.0	2.5	---	---	Low expansion where cracks or stresses must be limited
Resistance to Termites, Fungi	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good resistance
Dimensional Stability	Fair	Fair	Fair	Fair	Good	Good	Good			Good
Maximum Service Temperature, ° F	200	250	165	165	200	250	350	150-225	180	Minimum about 160° F for building construction
Fire Resistance	← Can be made self-extinguishing →									Self-extinguishing
Typical Wholesale Price[6]										
Dollars per 1000 bd. ft.	[2]150	---	$90	$90	---	---	---	---	---	
Thermal Cost Index ($/1,000 sq.ft., ru)	18 - 25		21-23	25	---	---	---	---	---	

[1] Data from "Foamed Plastics Charts," Modern Plastics Encyclopedia, 1964 and 1965.
[2] Polystyrene, polyvinyl chloride, cellulose acetate and epoxy types have "closed" or "open" cell types.
[3] Epoxies up to 35 lb. density and some high density polyurethanes have greater strength and somewhat lower insulating value (k = 0.36).
[4] ASTM D-2125-62T, 5% deformation.
[5] Fluorinated hydrocarbon (with vapor barrier); k = 0.12 initially.
[6] Prices vary widely. TCI values for polyurethane and extruded polystyrene are for gas-blown types.

1. Density and Thermal Resistivity. Insulation boards are produced in a wide range of densities to meet a variety of end-use demands in building construction. Semi-rigid softboards, such as foams, have densities ranging from 1.0 to 9 lb. per cu. ft., and resistivities ranging from 8 to 3 ru per inch.

   Rigid types, exemplified by vegetable and mineral fiber boards, cork, and cellular glass have densities ranging from 6 to 25 lbs. per cu. ft. and have thermal resistivity values ranging from 4.0 to 1.8 ru per inch. Densities of the so-called "intermediate" types of wood fiber board range from 25 to 50 lb. per cu. ft. and resistivity values from 2.5 to 1.3 ru per inch (the latter is a typical figure for plywood). Hard fiberboard may have a density up to 66 lb. per cu. ft., at which point its resistivity is about 0.7 ru per inch.

   In general, the higher the density, the lower the thermal resistivity and the greater the structural strength value are apt to be. Other factors, such as the amount and type of binder, hygroscopicity, capillarity, the diameter of the fibers or cell size of foamed materials, also may affect both density and thermal value, and the mechanical properties as well.

   From the practical standpoint, boards with resistivity values below 2.0 and with densities in excess of about 30 lbs. per cu. ft., are employed primarily for structural reasons. Their insulating values are of secondary importance. Thus, natural hard woods, having an average density of about 44 lbs. per cu. ft., and a typical resistivity of 1.1 ru per inch,[6] are being replaced in many uses by adequate and cheaper man-made products. The natural soft woods, with densities in the range of 26 to 39 lb. per cu. ft. have an average resistivity of about 1.3 ru per inch. Cork board, no longer manufactured domestically though at one time the only acceptable board with high insulating value (resistivity = 3.3 to 3.7 ru per inch), still is considered a known standard by a great many contractors and the general public.

   Expanded plastic foams (molded or extruded) with densities ranging from 1 to 5 lbs. per cu. ft. and with resistivities ranging from 8 to 3.3 ru per in., are continuing to grow in favor for many thermal insulation uses. As with fiber-base boards, strength values of a given foam increase with density.

   Plastic foams blown with a low-conductivity gas, such as a flourinated hydrocarbon, exhibit greater resistivity values (i.e. lower k-values) than those filled with air or carbon dioxide. A thermal resistivity of about 8 ru per in. is perhaps the maximum potential for the gas-filled products. This makes them particularly desirable for applications where space is at a premium, as in household refrigerators, transportation equipment, mobile homes, etc. The slow drop of resistivity to about 6 ru per in. has been mentioned earlier.

2. Thermal Resistance of Boards. Most of the structural boards and slabs that possess saleable insulating values have a thermal resistivity of at least 2 ru per inch of thickness, and rarely less than 2.5 ru per inch. There is a trend among producers of insulating boards to describe their products in terms of thermal resistance or thermal conductance (C = 1/R) for the thickness as marketed. This presumably helps to avoid confusion that may result from price comparisons between one product and another with essentially the same k-value but having a different thickness.

3. Water Absorption and Vapor Permeability. Most boards made from cellulosic fibers possess hygroscopic properties and can hold up to about 20% of moisture (by weight). Hygroscopic moisture has little effect on their insulating value.

   "Water absorption" refers to liquid water, which is retained in a capillary structure after it is wetted. ASTM Test Method C209-60 provides that (fiberboard) insulation be submerged for two hours, and its water retention observed. Under those conditions,

[6] Average from the publications of the USDA Forest Products Laboratory. Also, it should be noted that the conventional one-inch thick lumber board is 25/32 inches thick and therefore has a lower resistivity than those quoted above.

ASTM Specification C208-60 limits the volumetric gain of fiberboard sheathing to 7%, but allows 10% for roof insulation and interior finish.

Mineral wools are not sponge-like, but are wettable and will retain water in a similar test--the amount depending on fiber size, density and the characteristics of the binder used in the boards.

The water absorption behavior of insulation may be important if it is exposed to rain or snow, but good design and assembly of a building should keep the insulation dry in service. Good design means that the water vapor permeability of the insulation and all other parts of the assembly, including the vapor barrier, must be properly considered. Low permeability of the insulation is desirable in some applications, but low permeability (not actually zero perm-inch) may require a better vapor barrier if no condensation in the insulation can be tolerated.

For example, BRAB Report No. 38 (5) found the average moisture content of polystyrene core samples taken from existent cold storage warehouses (that had no vapor barriers) amounted to 40% by weight (approx. 1.3% by volume). The big differences between 40% and 1.3% reflect the differences in density between water and foam.

4. Resistance to Vermin, Decay, and Mold. Materials such as mineral wools, glass fibers, most plastic foams, cork, and redwood bark are inherently highly resistant to decay and mold, free from contaminating odors, and in board form provide no harboring place for vermin. Vegetable fiber boards must be treated during their manufacture, and almost invariably are treated to resist attack. Commercial binders and impregnants such as asphalt, inorganic cements, and phenolic resins, are also highly resistant to attack and to normal aging conditions. But only certain plastic foam products, cellular glass blocks or cellular rubber are satisfactory for perimeter or below ground-level structural insulation.
5. Dimensional Stability. Tolerances of plus 1/4 inch and minus 1/8 inch in lengths plus 1/4 inch and minus 1/8 inch in widths and plus or minus 1/16 inch in thickness are normally permitted. The temperature coefficient of linear expansion of cork board is about 3.5×10^{-5} in./in./^{o} F. Most plastic foam boards have even lower values. That of cellular glass is 0.46×10^{-5} in./in./^{o} F.

   The moisture coefficient of linear expansion may be more important, especially for hygroscopic materials. A moisture gradient in board insulation, and particularly roof insulation, may cause it to warp or buckle during application, or in normal service life if it is not adequately restrained and/or protected.
6. Maximum Service Temperature and Fire Resistance. For most building applications in which boards are used, a maximum service temperature of 200^{o} F. is adequate. While the upper temperature limit of unbonded glass fibers may be as high as 2000^{o} F., the temperature limit of bonded fibrous glass or mineral wool felt in board, block (or even blanket) form is limited by the bonding agent used; with phenolic resin type binders the maximum temperature may range from 450 ^{o}to 500^{o} F.

   Most government specifying agencies now require a flame-resistant rating for interior finish materials of various degrees, depending on the particular area of the building or type of occupancy in which the interior finish is used. The flame spread is generally determined under a standard test method for surface burning characteristics of building materials (ASTM E-84-61). This is actually a comparative method in which a select-grade red oak flooring is arbitrarily given a flame-spread rating of 100 (19.5 feet in 5.5 minutes under test conditions). Some agencies also place limitations on smoke, which is also determined by this test method. The smoke rating for the red oak flooring is arbitrarily set at 100 while that of an asbestos-cement board is rated at zero to provide a scale of comparison. (For additional information see publications of the National Fire Protection Association (2).

   Materials that are concealed, such as sheathing, lath, studs, and joists and flexible and fill insulation contribute little or no fuel to a fire in the average home until the

interior walls are burned through or sufficient heat is developed to reach ignition temperature. Indeed, insulation will not transmit heat as rapidly as more highly conductive materials and can thus slow down the rate of spreading of a fire. Furthermore, all factory-finished structural insulation boards designed for interior finish have flame-resistant surfaces which retard the spread of flames on walls and ceilings of that material (15).

Most plastic foam insulations soften and melt at 200°-300° F. and will burn unless they are treated with a fire-retardant material or protected by a suitable paint. Furthermore, since some of the organic foam materials are thermoplastic, they cannot be used continuously at temperatures above 175° F, which restricts their application to residential and low-temperature uses. Some foams may release toxic gases such as carbon monoxide or otherwise objectionable odors under combustion conditions, a drawback that must be considered in fire control.

7. Compressive Strength and Tensile Strength. Both these structural strength characteristics affect load-bearing capacities. In general, these strength characteristics increase with density, and in man-made insulating materials are dependent upon the type of base material and binding agent employed.

   The compressive strength of rigid insulation products is usually measured in terms of pounds per square inch (psi) at a maximum load, or at a specified deformation, usually 5 or 10%. For thermal insulation, most values are in the range of 5 to 100 psi.

   The modulus of rupture of structural insulating boards varies from 250 to 700 psi and the modulus of elasticity in bending from 25,000 to 90,000 psi. Most building lumber has a modulus of rupture in the range of 5,000 to about 18,000 psi and a modulus of elasticity in bending in the range of 800,000 to 2,100,000 psi. The modulus of elasticity for polystyrene foams ranges from 900 to 5,300 psi, while that for polyurethane foams may range from 5,000 to as high as 36,000 psi. (14).

   The values in tables 8 and 9 indicate fiberboard and cellular glass insulation materials have strength characteristics greatly below those of building lumber. The low density foam and non-load bearing types of insulation are also appreciably weaker.

   Compressive and tensile strength properties are more important than thermal properties where structural strength is required. Consequently, boards and slabs compete with one another but not with batts, blankets, and loose-fill insulations that are designed solely for thermal values. Plastic foams, on the other hand, not only compete with boards, batts, and blankets in building construction but also in the appliance, transportation equipment, and prefab housing field where high thermal resistivity, light weight, and some structural strength values are all important.

8. Miscellaneous Aspects. Different end uses demand different combinations of properties. Two examples follow:

   a. Flat Roofs. Figure 6 shows a schematic design for a flat roof insulated construction where load-bearing values as well as the overall thermal transmittance, "U," must be considered. If we assume that a total resistance R = 8.5 ru is required (U = 0.12), the insulation resistance to be installed should equal R = 8.5-5.77 = 2.73 ru. This requires approximately one inch of roofing insulation (18). Use of a deck with lower insulation resistance, such as one of steel or concrete, would necessitate use of a greater thickness of insulation, perhaps twice as thick.

C. Structural Panels

Structural panels, as defined for this report, consist of large prefabricated building units made up of two or more components. They may have several functions, but the two major ones are weather protection and ability to carry certain design loads. They can be produced most

ROOF INSULATION DESIGN

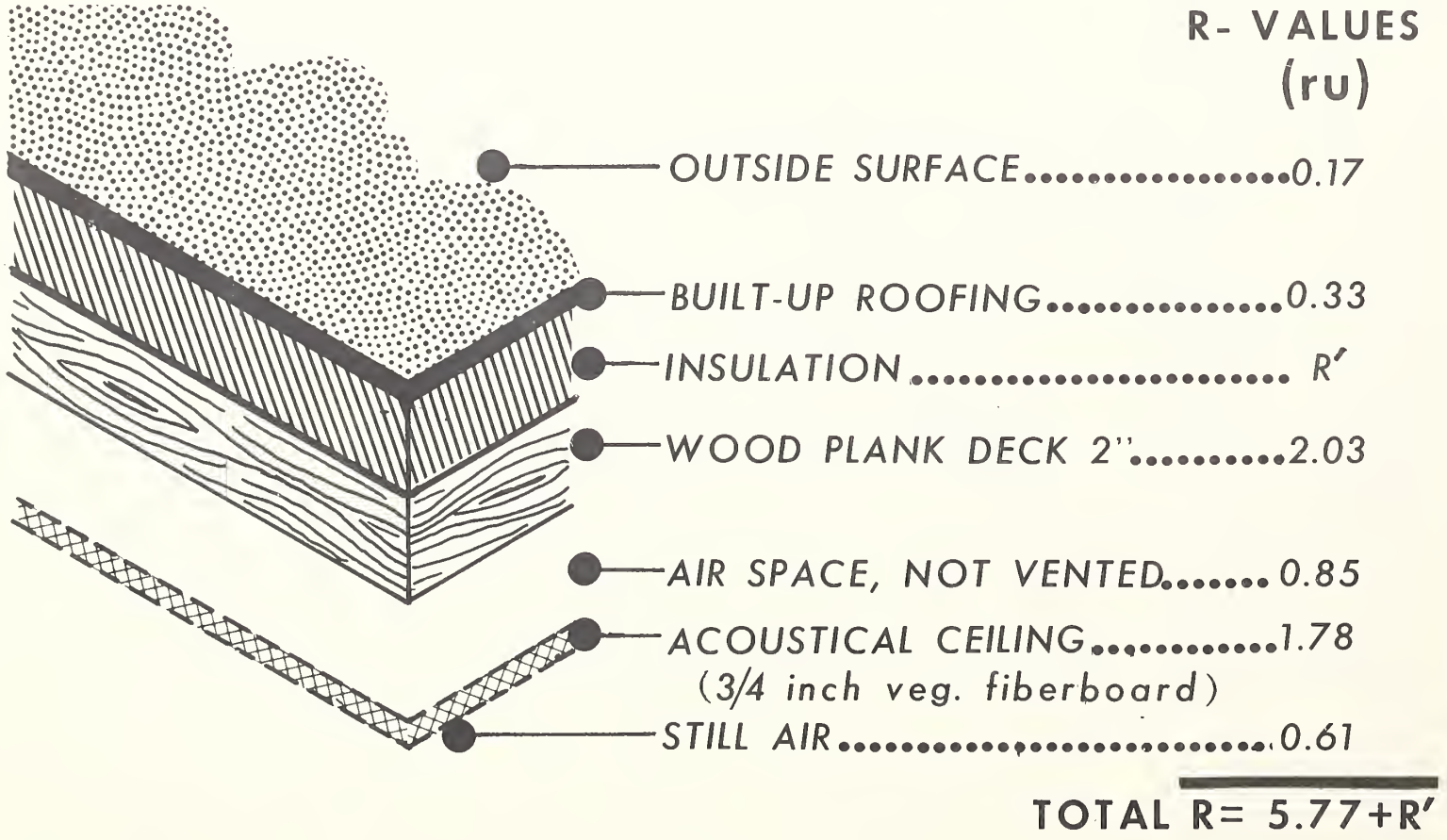

Figure 6

economically when there is a great deal of duplication, as in the construction of standardized homes and large buildings, or in the manufacture of large refrigerators and transportation equipment.

These panels have a sandwich type construction with strong exterior faces separated by a thicker, but lightweight, insulating core material. Various facing materials such as plywood or metal sheets and various cores with a fibrous or plastic foam structure are employed, often with a bonding adhesive. The semi-rigid core stiffens the structural faces, provides thermal insulation, and may be designed for condensation control. For stiffness, the core material should be sufficiently compressible so that, when pressed between sheets, it conforms tightly and uniformly to permit good bonding of the components.

The combined functions of insulation, vapor barrier, and light washable interior finish are provided by some block and board panel constructions.

Other variations include precast concrete slabs backed by plastic insulation boards, pressed-wood boards with a balsa core, panels using metal frames with polyester resin-glass fiber laminates, etc. All-plastic structural panels using stiff plastic sheets for the faces are in developmental stages.

Listed below are the general requirements of insulation material that is to be used as the core in sandwich-panel construction:

(1) Low density, preferably in range of 1 to 4 lbs. per cu. ft., for ease of handling and to reduce cost of construction and shipping.
(2) Low conductivity (high resistivity) to minimize thickness and increase usable space within the structure.
(3) Dimensional stability in the normal temperature range and in other environmental conditions of use.
(4) Low water absorption if rain leaks are possible.
(5) High compressive strength to reduce weight and cost of faces.
(6) High modulus of elasticity.
(7) High impact strength to reinforce faces.
(8) Resistance to insects, mold, and fungi.
(9) Noninflammable or fire retardant.

Some of these features can be improved only by sacrificing other features. A compromise is inevitable, but the cost of the total panel and the structural requirements are always decisive factors.

D. Block and Pipe Insulation for High Temperature

Rigid inorganic block insulation is supplied with plane surfaces and in various other shapes. It is molded or cut into cylinders, half cylinders, or curved segments for use on piping, and into flat or curved blocks for vessels and large equipment. The principal raw materials employed in making block insulation are asbestos fiber, calcium silicate, diatomaceous silica, expanded silica, 85% magnesia, and cellular glass and fibers of rock and slag or glass. These products are particularly suitable for use on irregular surfaces and at temperatures above the range for ordinary organic insulation materials (see table 10 which includes organic materials for comparison).

Inorganic materials are popular because of their structural properties, low thermal conductivities, high temperature tolerance, and incombustibility. The finished products are frequently blends of materials, usually with inorganic cement binding agents. The various compositions or formulations are dictated by specific end-use requirements. Insulating cements mixed with water for application by trowel are also important for special shapes, supplementing block insulation.

Some of the properties of block and pipe insulation materials are shown in tables 10 and 11. Blanket type industrial pipe insulation materials designed for maximum service temperatures below 500° F. have been previously discussed in Section VI "Batts and Blankets." The supporting jackets, vapor barriers for low temperatures, etc. that such uses require will not be discussed.

TABLE 10.--Properties of High Temperature Pipe Insulation[1]

(Data from July 1, 1961, issue of "Chemical Week")

Type	Max. service temperature	Thermal conductivity (k)[2]	Popularity status
Calcium silicate.....	1,200° F.	0.46 @ 400° F.	Use growing, most popular insulation material in CPI.
Glass fibers.....	450° F.	0.35 @ 300° F.	Use growing but limited to medium-low temperatures (also for dual temp. lines, etc.).
Bonded perlite.....	1,500° F.	0.45 @ 400° F.	Use growing, aided by quality improvements.
Mineral wools.....	1,000° F.	0.40-0.45 @ 400° F.	Use growing, particularly where flexibility is desired at high temp.
Diatomaceous earths.....	1,900° F.	0.69 @ 400° F.	Use declining. Losing ground to glass fibers and silicate.
Magnesia (85%).....	600° F.	0.46 @ 400° F.	Use definitely declining. Virtually displaced by glass fibers, calcium silicate, etc.

[1] See table 11 for additional data.
[2] Pipe temperatures are shown.

TABLE 11.--Properties of Inorganic Block Insulation For High Temperature Use

Property	Calcium silicate[1]	85% Magnesia[2]	Diatomaceous earth[3]	Cellular glass[4]
Density, average lbs./cu. ft. maximum.....	14.0	13.0	24	8-10
Thermal conductivity (k) at mean temp. of:				
300° F.....	0.50	0.46	--	0.55
500° F.....	0.60	--	0.70	--
700° F.....	0.71	--	0.75	--
Compressive strength, ave. at 10% deformation:				
minimum psi., when dry.....	[5] 50	50	[5] 65	100
after 16 hr. water immersion.....	25	--	--	--
Flexural strength, ave. psi., minimum.....	42	39	60	75
Linear shrinkage after soaking heat for 24 hours at:				
1200° F., ave. %, maximum.....	2.0	--	--	--
600° F., ave. %, maximum.....	--	2.0	2.0	0

[1] Federal Spec: HH-I-523a and ASTM: C344-60T.
[2] ASTM Specification C489-62T.
[3] ASTM Specification C333-59T, Class I.
[4] ASTM Specification C343-56.
[5] At 5% deformation.

In addition, it is not necessary to discuss in detail the properties of inorganic insulating blocks and pipe insulation designed for use at temperature extremes (-300° F. or +300° F.). Opinions on piping insulation are presented in BRAB Report No. 41 (5a).

E. Economics

The wholesale price to distributors for most lumber and insulation board may be quoted in cents per board foot, dollars per 1000 board feet, or dollars per 1000 square feet of a specified thickness and "C" value. The price depends primarily on the competitive situation, but the following factors are or major importance in the price of insulation board:

1. Thermal conductivity (C- or k-value).
2. Board area and thickness.
3. Structural properties.

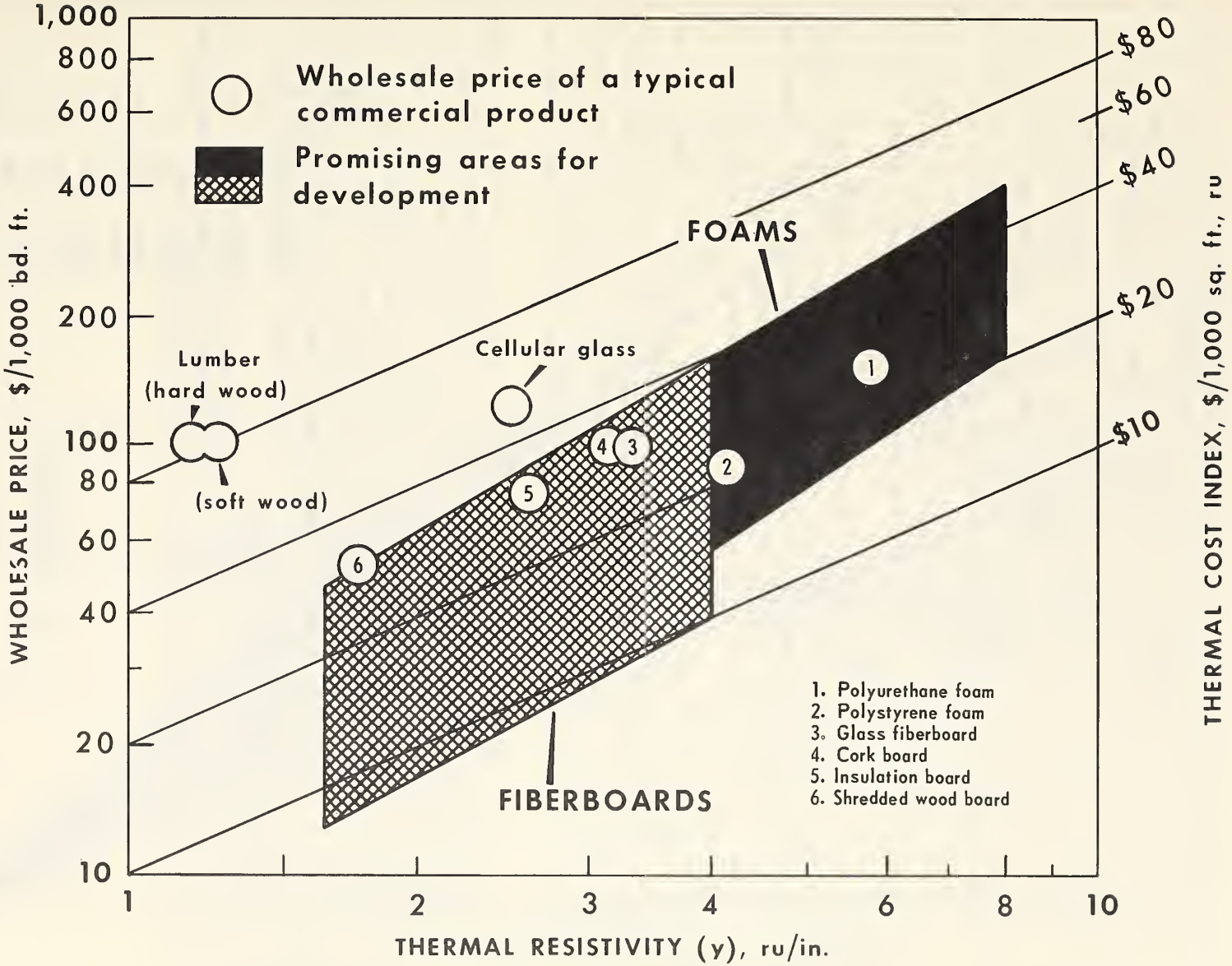

Figure 7. --Cost of rigid insulation.

4. Type of finish (vapor barriers or other coverings, beveled edges, etc.).
5. Nature of basic material (mineral, vegetable, plastic, resistance to vapor, etc.).
6. Board construction (homogeneous or laminated, with or without binding agent, etc.).

From the standpoint of thermal values, it is useful to convert prices of boards with similar structural values to the same common denominator (Thermal Cost Index) used in comparing the costs of batts, blankets, and loose-fill insulation, measured in "dollars per 1000 sq. ft., ru."

The lines of constant TCI value in figure 7 show how the competitive selling price per 1000 board feet is affected by the thermal resistivity (y = 1/k) of the material. For example, a rigid plastic foam with adequate structural strength for a particular end use could probably sell in the price range of $200 to $350 per 1000 board feet if it had a resistivity of 8 ru per inch or more. A higher density, tougher product with a resistivity of 4 ru per inch would be worth some price below $150 per 1000 board feet. Cellular glass, for example, with its superb resistance to fire, water, air, termites, fungi, etc. can sell for a higher price than any foamed plastic or insulation board of equivalent resistivity.

Looking at the curves in another way, for the price of $100 per 1000 board feet one might purchase lumber with a thermal resistivity of 1.1 ru/in. or cork board with a thermal resistivity of 3.7, or a glass fiberboard with a resistivity of 3.7, or rigid polystyrene foam with a resistivity of 4.3. If maximum strength were required, the choice would be lumber, but if no strength were needed, the choice would probably be polystyrene. All properties of each insulation may be considered in the choice.

Competition forces materials with similar end-use values to be competitively priced. This can be demonstrated by pointing out that it takes a 1½-inch thick fiberboard (k = 0.36) to match the thermal insulating value of a 1-inch thick plastic foam (k = 0.24), or of a three-quarter-inch thick plastic foam with a k factor of 0.18. The 1½ inch fiberboard sells for approximately $70 x 1½ = $105 per 1000 square feet, 1½" thick. A typical foamed-plastic product with a k-factor of 0.23 to 0.24 sells for just about $100 per 1000 board feet, illustrating the competitive relationship.

Figure 7 also shows "promising areas for development." As similar charts show regarding loose-fill and blanket-type insulation, figure 7 shows the upper and lower price boundaries as parallel. Increases above the TCI line are based on the fact that thinness of the insulation commands a higher price in many applications where space is valuable. Furthermore, figure 7 shows that foamed plastics can reach values that fiber insulation cannot attain. The higher thermal resistivity values (and potentials) are made possible by use of closed cells filled with a gas other than air. Not shown, but probably obvious, is the fact that plastic foams can be produced with resistivities below 4 ru per inch, if greater strength characteristics are of major importance. The potential price range then is dependent on structural and other properties that are more competitive with those of fibrous types of insulation.

In any event, a newly developed product can attain major commercial success only if it provides the same desirable combination of properties as an established one but at a lower price, or if it has a superior combination of properties at the same established price level.

IX. SUMMARY

The products discussed in this report find commercial outlets because they (a) offer resistance to the natural flow of heat, (b) are available at competitive costs, and (c) may offer additional values, such as structural strength.

The published literature contains comparisons of the thermal and physical properties of many kinds of thermal insulating materials. From such data it is possible to prepare such charts as figure 8, which shows the insulation thickness required to attain a needed thermal resistance

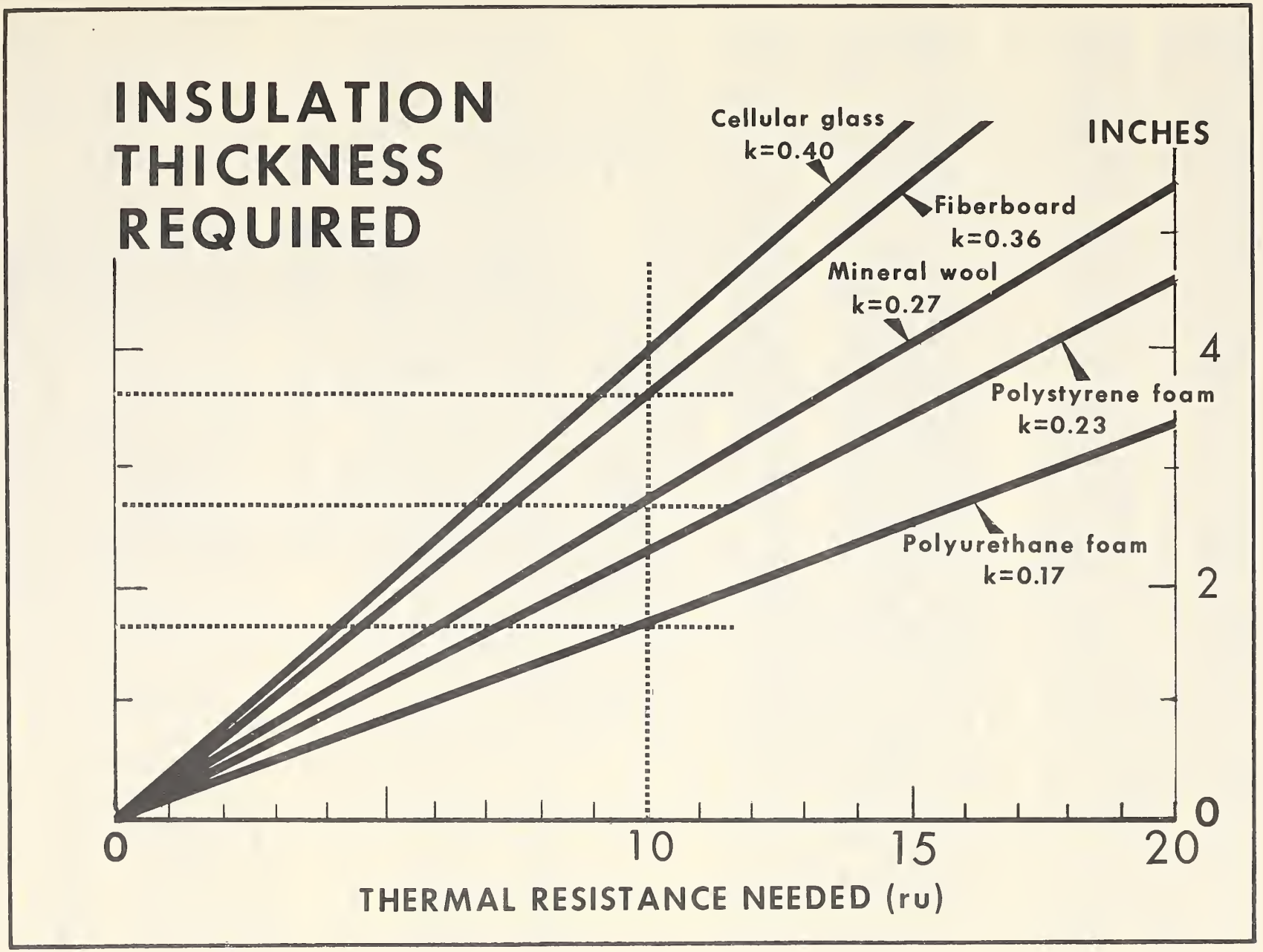
INSULATION THICKNESS REQUIRED
Cellular glass
k=0.40
Fiberboard
k=0.36
Mineral wool
k=0.27
Polystyrene foam
k=0.23
Polyurethane foam
k=0.17
INCHES
4
2
0
0
10
15
20
THERMAL RESISTANCE NEEDED (ru)

Figure 8

value. For example, if the design requirements call for use of an insulation having a value of R=10ru for a certain area of a building, figure 8 shows that about 1.7 inches of polyurethane foam, or 2.7 inches of mineral wool, or 3.6 inches of wood or cane fiberboard are needed. Such information does not reveal which of these materials would cost the least or would be best for reasons other than insulating value.

The characteristic features and selling prices of various types and forms of insulation materials can be listed in a similar way. Each bit of information helps not only the prospective buyer but also the researcher who is interested in the possibility of devising a commercially feasible agriculture-based thermal insulating material.

A. Price-Property Comparisons

Depending upon the physical form of the end product, prices of insulating materials are normally quoted in dollars per (1) 1,000 board feet, (2) 1,000 sq. ft. of a specified thickness or "R" value, (3) bag, or (4) cubic foot. In order to compare these prices for the different types and forms of insulation, it is first necessary to recalculate the quoted wholesale prices to a common base, and then to introduce a new device, combining price and thermal resistivity. The new device is the "Thermal Cost Index" (TCI), and is designed to serve as a common denominator for the various products.

Table 12 is a comparison of prices and other features of various types of insulation. Wide variations in prices are noted between the different types and forms of insulation. For instance, most structural (rigid) boards are selling for about $80 per 1000 board feet, while loose fill (used

TABLE 12.--Typical Wholesale Prices and Features of Insulating Materials

Type of product	Approximate price in dollars per 1000 bd.ft.	Thermal cost index in dollars per 1000 sq.ft., ru	Thermal conductivity k-value	Structural strength	Remarks
Cellular Glass.....	120	46	0.39	Good	No moisture absorption or vapor transmission. Used especially where good, low-temperature vapor resistance and structural properties are needed.
Wood or Cane Fiber Boards.....	70-80	25-32	0.34-0.38	Good	Strength plus important insulating values. Usable for many purposes in building construction.
Inorganic Fiber Boards	100	27-30	0.27-0.30	Fair	Lightweight is valued for roofs, sandwich panels and transport vehicles. Spongy but tough and durable, fire-resistant.
Foamed Plastics.....	90-150	21-25	0.12-0.28	Fair	Very light and versatile Lowest k-values may increase with age.
Batts & Blankets.....	15-25	4-6	0.25-0.30	None	Excellent low cost insulation when properly installed.
Loose Fill.....	4-10	1.3-3	0.28-0.48	None	Lowest in cost, but if used to completely fill wall cavities, it can be a problem. Used mostly for ceilings and the frame walls of old houses.
Lumber[1] (soft wood)..	100	76	0.76	Excellent	Insulating value important but is secondary to structural value.

[1] Included for comparison only.

largely for ceilings and for older houses) can be purchased for the equivalent of $4 to $10 per 1000 board feet. The difference is due, at least in part, to the fact that insulating boards provide structural as well as thermal properties, while loose fills (as well as batts and blankets) have no structural value.

Based upon insulating value only (TCI) and disregarding structural properties, loose fill provides the lowest cost insulating material at about $1.30 per 1000 sq. ft., ru. This compares with about $76 per 1000 sq. ft., ru for softwood lumber, which, of course, is primarily a structural material, with "plus value" as insulation value. Figure 9 shows comparative TCI values for typical insulation materials, with values for representative softwood and hardwood lumber included for general comparison. These values give no indication of cost of installing the products, which is an important consideration.

In figure 10 the price and resistivity relations for all types of insulation are shown. Within each group the selling price per board foot normally decreases with lower resistivity. For instance, a typical mineral wool blanket priced at about $15 per 1000 board feet ($45 per 1000 sq. ft. for a 3-inch thick blanket with R=11 ru) has a resistivity value of 3.7 ru per inch. According to figure 10, a blanket with a resistivity of only 2.5 ru per inch would be competitive if priced at $10 per 1000 board feet. However, for some applications, high resistivity is demanded because of limited space and this need will in some cases permit a price somewhat higher than the TCI value indicates.

Figure 10 also shows the "promising areas for development" of insulation materials. For clarity, no overlap of areas is shown, though overlap is quite possible. The choice of boundary lines is governed by the following factors:

(a) Thermal resistivity of fibrous materials has a virtual maximum of 4 ru per inch. "Closed cell" foams may reach 8.
(b) Existing competitive material properties
(c) Known possibilities for improvement
(d) Assumption that doubling the thermal resistivity will justify a 25% increase in the Thermal Cost Index
(e) Unsatisfied demand areas.

Several comments on this figure and earlier ones of a similar nature are in order. Equal areas on the chart do not suggest equal scope or opportunity for development. The use of logarithmic scale makes the "Batt-and-Blanket" area appear equal to the "Loose-Fill" area, but actually it is twice as large. And the area for closed cell foams is nearly 100 times larger than that of loose fill. The areas for fiberboards and blankets do not overlap, because a rigid board normally costs more to produce than a blanket of the same resistivity. However, the lowest priced board might sell for less than the highest priced blanket because the board would have structural strength but perhaps only 40% of the resistivity of the blanket. A similar comparison could be made of ordinary lumber and a low-density, high-resistivity type of plastic foam.

B. Possible Areas for Utilization Research

Agricultural raw materials are organic in nature and are therefore not suitable for the production of insulating products requiring relatively high temperature stability such as asbestos, calcium silicate, cellular glass, etc. For this reason it would seem that greater success in utilization research could be achieved by confining the efforts to the development of insulating materials designed for use at temperatures below 250° F. A particularly interesting field appears to be insulating materials for homes and industrial buildings. The current sales of insulating materials in this market are about 300 million dollars annually and destined to increase.

The ramifications and possibilities of combination products and dual purpose products deserve consideration, particularly when costs of application of two items in a single wall or ceiling may be involved. A case in point is the structural sandwich. Others suggested by W. C. Lewis (13) are combined siding-sheathing and structural insulating roof deck.

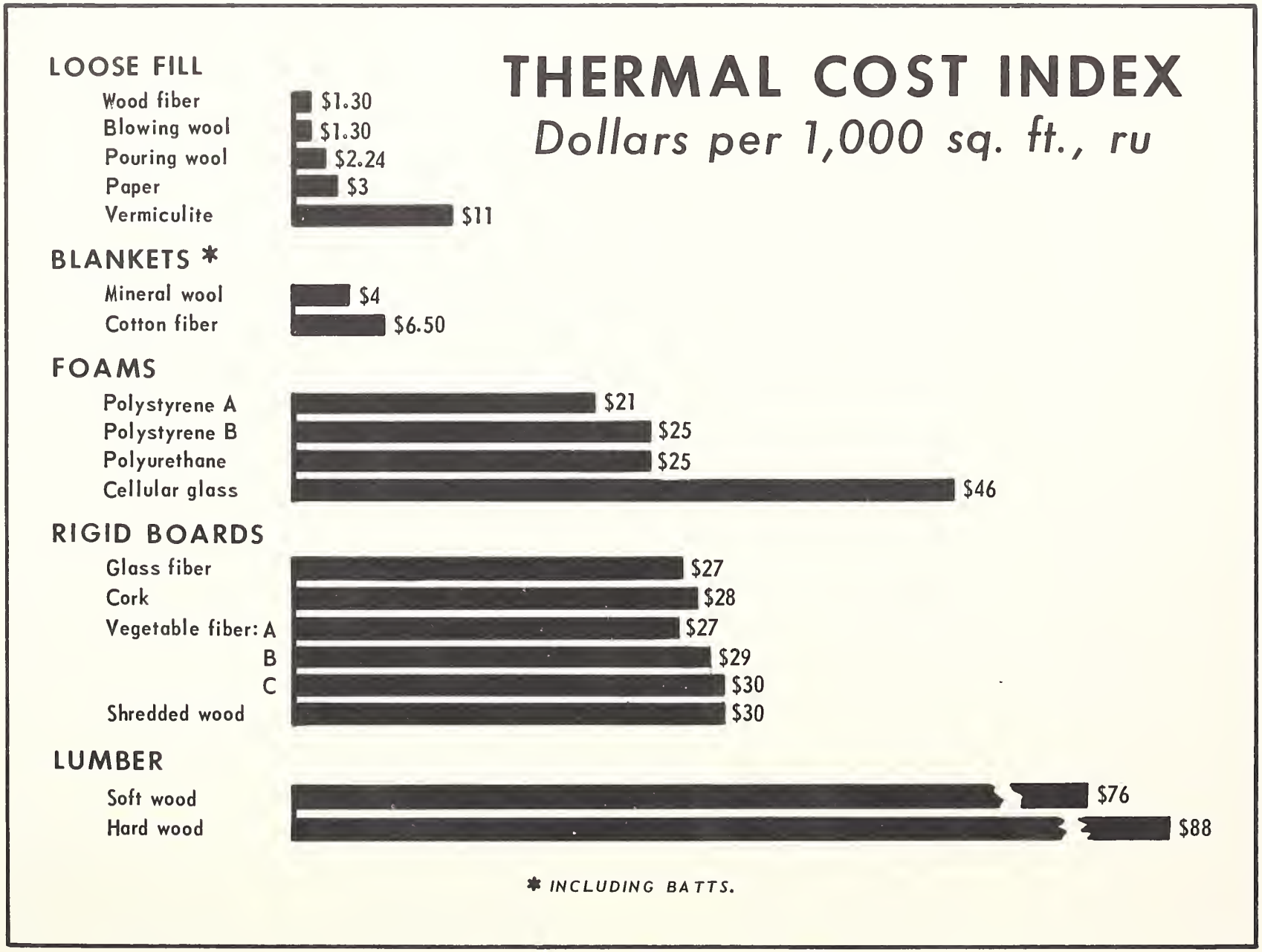
THERMAL COST INDEX
Dollars per 1,000 sq. ft., ru
LOOSE FILL
Wood fiber
Blowing wool
Pouring wool
Paper
Vermiculite
$1.30
$1.30
$2.24
$3
$11
BLANKETS *
Mineral wool
Cotton fiber
$4
$6.50
FOAMS
Polystyrene A
Polystyrene B
Polyurethane
Cellular glass
$21
$25
$25
$46
RIGID BOARDS
Glass fiber
Cork
Vegetable fiber: A
B
C
Shredded wood
$27
$28
$27
$29
$30
$30
LUMBER
Soft wood
Hard wood
$76
$88
* INCLUDING BATTS.

Figure 9

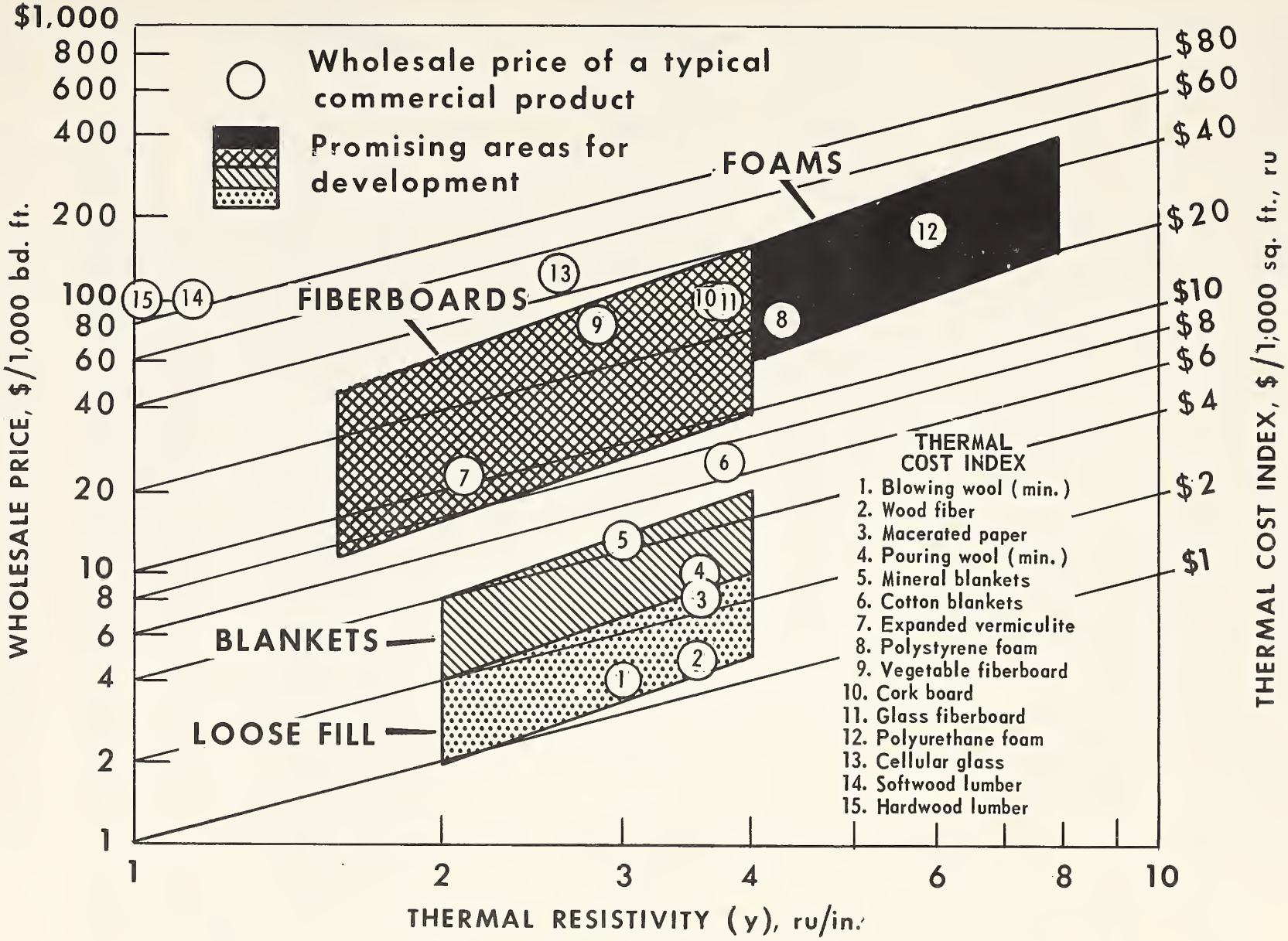

Figure 10.--Insulation costs.

1. Fibrous Materials. Most insulations have fibrous structures, although cellular structures have also been available in cork, glass, expanded rubber, and minerals before the advent of plastic foams. Air is the real insulator in fibrous materials and its conductivity (k-value) at 75° F. is about 0.18 BTU per hr., sq. ft., (deg. F. per in.), which definitely limits the thermal resistivity value of air filled materials.

Heat is also transferred by air convection, and felted fibers block this movement in large measure, depending on their spacing. Close spacing of fibers also reduces heat transfer by radiation within the insulation itself.

However, as spacing is reduced, there is more conduction by the solid fibers unless their size is also reduced. Bonding the fibers, one to another, also increases solid conduction and is avoided where rigidity is not required. Progress has been made in these directions, and a k-value as low as 0.22 (a resistivity of 4.5 ru per inch) has been obtained with very fine glass fibers in a density around 2 lbs. per cu. ft. At present, however, the k-value of fibrous type building insulation practically never goes below 0.25. A resistivity of 4 ru per inch is therefore the current practical maximum value.

High resistivity of an insulation is desirable, but it is not necessary for many building applications in which there is space for a thicker insulation that can be more cheaply produced. It makes little difference in the ceiling of most homes whether the 12 ru of needed insulation is obtained in 3 inches of 4 ru per in. insulation, or in 6 inches of 2 ru per in. material. In fact, if the insulation is placed between ceiling joists, the effective resistance of the whole area (including joists) is greater in the latter case. Thus, it is evident that a fibrous material of almost any k-value should be saleable if the price is right.

The only fibers of agricultural origin now commonly used are those of wood, sugar cane, and cotton. These may be byproducts, which retain their natural plant fiber structures. In the development of a new product, first consideration should be given to all waste agricultural materials, with or without chemical modification of their fibers. Corn, wheat, and other grains, when harvested, leave an abundance of fiber with little known commercial value. These waste products have always been used somewhat inefficiently as insulation in thatch and in bedding for both man and beast. While work has been done in this area, it seems possible that with imaginative processing grain waste should have commercial value in some insulation markets--especially near the source--and in animal housing, a market that is becoming increasingly important.

Resistance to fire, vermin, and fungi are needed factors that can be readily provided. Vapor control may be quite important in a farm structure housing animals and poultry, because of the great generation of moisture by the stock. But vapor control is not a major problem in most buildings with the technology now available.

2. Foamed-Type Materials. There is a growing demand for foamed-type, closed-cell materials of low k-value (preferably k = 0.25 or lower) and with cell walls impervious to the blowing agent. Some of the best polyurethane foams with fluoro-carbon filled cells deteriorate in k-value because of slow leakage of the blowing agent and/or inward diffusion of the lighter gases of the air. Foamed materials in board form with k-values of 0.23 are sold for about $90 to $100 per 1000 board feet. Fluoro-carbon filled foamed materials can be made with k-values as low as 0.11, but current experience indicates the k-value stabilizes at 0.15 to 0.17. If the 0.11 value could be maintained indefinitely without deterioration, a price of $200 or more per 1000 board feet could probably be justified for certain applications, as evidenced by the current level of $150 per 1000 board feet for a polyurethane foam with an ultimate k-value of 0.17 or less.

The need for greater fire resistence is one additional factor that must be considered to insure greater penetration of both the home and marine construction markets of the future. This need must, of course, also be met by other insulation products, including resin-bonded materials.

C. Special applications

The insulation of refrigerated buildings involves unique problems of moisture control. In most other structures vapor that enters and condenses in a wall during the winter months (though hazardous to the structure) is removed through evaporation on warm summer days, and thus the dryness that is essential in insulation is restored. In contrast, the cold side of a refrigerated wall is always cold, and water vapor that enters on the warm side often condenses and increases in quantity in the colder parts of the wall until the thermal value of the insulation is lost or the wall is wrecked by the expansion of freezing water.

Long life and proper operation of a building held below zero F. requires essentially total exclusion of water vapor from the insulation by a warm-side vapor barrier that is vapor tight and air tight. No insulation now available except cellular glass has sufficient vapor resistence, and this material also fails if its joints are imperfect.

This refrigeration market is open to new insulations and new techniques for applying them. A sprayed foam, covered on the warm side by a sprayed vapor barrier both without joints, would have real merit. With new and replacement construction of cold storage facilities likely to match the past decade's sevenfold expansion within the next 10 to 15 years, the potential demand for improved methods is great.

Similarly, there are virtually untouched market potentials for a tough spray-on insulation in the air conditioning field, for external application to ducts and pipes that carry air or liquids at temperatures below about 300° F. Furthermore, many hospitals may have miles of pipes and ducts, to carry air, oxygen, nitrogen, water, etc., utilizing thermal-acoustical coatings which are usually difficult to maintain or replace.

Increasing use of electrical heating in residential homes suggests another important market. The higher BTU/hr. cost of electricity compared to coal, oil, or gas makes the reduction in heat loss an important economic consideration. Instead of the conventional 2 to 4 inches of typical insulation, perhaps as much as 8 to 12 inches would be justified. This poses problems either in the space for this insulation, or improvements in its effectiveness (16).

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